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REPORT

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GRANT NAGW-533

LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

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I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing atmospheric constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. For example, results obtained for the microwave opacity from gaseous H_2SO_4 under simulated Venus conditions, during the first two years of Grant NAGW-533, showed that not only was the opacity from H_2SO_4 much greater than theoretically predicted, but that its frequency (wavelength) dependence was far different than that theoretically predicted (Steffes, 1985 and Steffes, 1986). Subsequent measurements made by Steffes and Jenkins (1987), showed that the microwave opacity of gaseous ammonia (NH_3) under simulated Jovian conditions did indeed agree with theoretical predictions to within experimental accuracy at wavelengths longward of 1.3 cm. Work performed by Joiner et al. (1989) during the fourth and fifth years of Grant NAGW-533 and continuing into this past grant year (February 1, 1989 through October 31, 1989) has shown that laboratory measurements of the millimeter-wave opacity of ammonia between 7.5 mm and 9.3 mm and also at the 3.2 mm wavelength require a different lineshape to be used in the theoretical prediction for millimeter-wave ammonia opacity than had been previously used. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements and to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

A key activity for the past grant year has continued to be laboratory measurements of the microwave and millimeter-wave properties of the simulated atmospheres of the outer planets and their satellites. As described in the previous Semiannual Status Report #11 for Grant NAGW-533 (February 1, 1989 through April 30, 1989), initial laboratory measurements of the millimeter-wave opacity of gaseous ammonia (NH_3) in a hydrogen/helium (H_2/He) atmosphere, under simulated conditions for the outer planets were completed in 1988. These measurements were conducted at frequencies from 32 to 40 GHz (wavelengths from 7.5 to 9.3 mm). A complete description of this millimeter-wave spectrometer is given in previous Annual Status Reports for Grant NAGW-533, and in Joiner et al. (1989).

Since larger variations from theoretically-derived opacity values were expected at shorter millimeter-wavelengths (see de Pater and Massie, 1985), we have conducted laboratory measurements at wavelengths near 3.2 mm (94 GHz), where a large number of observations of the emission from the outer planets have been made. A description of this new system was presented in Semiannual Status Report #11 (February 1, 1989 through April 30, 1989). A better knowledge of the millimeter-wave absorption properties of NH_3 is essential, not only to help better characterize the distribution and abundance of ammonia at high levels in Jovian atmospheres, but to make it possible to resolve the contributions from other absorbing constituents such as H_2S (see Bezard et al., 1983). This knowledge will be of considerable importance for millimeter-wave instruments proposed for future missions, such as the MSAR (microwave and spectrometer and radiometer) proposed for the Cassini mission.

In some cases, new observations or experiments have been suggested by the results of our laboratory measurements. For example, this facility was initially developed, and then operated, in order to evaluate the microwave absorbing properties of gaseous sulfuric acid (H_2SO_4) under Venus atmospheric conditions. The results, obtained at 13.4 cm and 3.6 cm wavelengths, were applied to measurements from Mariner 5, Mariner 10, and early Pioneer-Venus Radio Occultation experiments, to determine abundances of gaseous sulfuric acid in the Venus atmosphere (Steffes, 1985). Further laboratory measurements also suggested that a substantial variation in the Venus microwave emission, related to the abundance of gaseous sulfuric acid, might exist near the 2.2 cm wavelength. Since no observations of the Venus emission at this wavelength had ever been published, we conducted observations of Venus using the 140-foot NRAO telescope and the 64-meter DSN/Goldstone antenna in April 1987 to not only search for the presence of the predicted feature, but to use such a feature to determine a planet-wide average for sulfuric acid vapor abundance below the main cloud layer. The results of this observation were substantial in that they not only placed limits on the abundance and spatial distribution of gaseous H_2SO_4 and SO_2, but they also suggested some limits to long term temporal variations for the abundance of these two gases.

Recently, we completed calibration and interpretive studies on the data from these observations and a paper entitled "Observations of the Microwave Emission of Venus from 1.3 to 3.6 cm," by P.G. Steffes, M.J. Klein, and J.M. Jenkins, has been accepted by the journal Icarus. One important issue which was discussed in this paper is the discovery that the microwave absorptivity for gaseous H_2SO_4 which was measured by Steffes (1985 and 1986) appears to differ from a theoretical spectrum newly computed from over 11,000 lines by Janssen (personal communication) by a scale factor. That scale fator suggets that the theoretically-derived "dissociation factor" for gaseous H_2SO_4 (i.e., the percentage of H_2SO_4 which breaks done to form SO_3 and H_2O) may have been underestimated. This results in an underestimation of the absorption from gaseous H_2SO_4. Therefore, an experiment has been conducted to correctly evaluate the "dissociation factor" and thus allow unambiguous calibration of laboratory data for H_2SO_4 opacity (see Section III). This will be critical for the proper interpretation of a wide range of opacity data.

Another important tool for evaluating potential spatial and temporal variations in abundance and distribution of gaseous H_2SO_4 is the reduction and analysis of recently obtained Pioneer-Venus radio occultation measurements. The 13 cm microwave absorptivity profiles, which can be obtained from the radio occultation data, are closely related to the abundance profiles for gaseous H_2SO_4. Starting in June 1988, we began the reduction of the 1986-87 Pioneer-Venus radio occultation measurements (working at JPL with support form the Pioneer-Venus Guest Investigator Program) in order to obtain the needed 13 cm microwave absorptivity profiles. Yet another important source of information is the increasing number of high-resolution millimeter-wavelength Venus emission measurements which have been recently conducted. Correlative studies of these measurements with radio occultation measurements and our longer wavelength emission measurements (Steffes et al., 1989) should provide the necessary data for characterizing temporal and spatial variations in the abundance of gaseous H_2SO_4 and SO_2, and for modeling its role in the subcloud atmosphere. However, unambiguous results will require that we have dependable knowledge of the equilibrium between gaseous H_2SO_4, SO_3, and H_2O, both so as to properly interpret laboratory measurements of the microwave and millimeter-wave opacity of the gases which elute from liquid sulfuric acid, as well as to model their relation within the Venus atmosphere. Our results in Section III provide this information.

Recently, we have developed models for microwave and millimeter-wave emission from the Jovian planets in order to evaluate how adjustments to ammonia abundance profiles affect the predicted emission spectrum. We have also compared these results with observations from earth-based radio telescopes. (In the future, we should be able to take advantage of the availability of data from several millimeter-wave radio telescope arrays in order to develop localized ammonia abundance profiles over the entire disk of one or more Jovian planets.) In the next year of Grant NAGW-533, we propose to use the results of our laboratory analysis of the millimeter-wave absorption from gaseous NH_3 under simulated Jovian conditions to complete a formulation which accurately predicts the opacity from gaseous ammonia in a Jovian-type atmosphere over the entire 1 mm to 20 cm wavelength range (frequencies from 1.5 to 300 GHz). Further discussion of this and other work related to the outer planets is presented in Section II. Likewise, we plan to continue to make laboratory measurements which will support our interpretive work of the 13 cm absorptivity profiles in the Venus atmosphere, which we are developing as part of the Pioneer-Venus Guest Investigator program, as well as interpreting microwave and millimeter-wave emission measurements of Venus. These data sets will be invaluable for characterizing the spatial and temporal variabilities of H_2SO_4 in the Venus atmosphere (see Section III). Finally, we will complete designs for laboratory instrumentation which will allow us to measure the microwave and millimeter-wave properties of liquids and solids under simulated planetary conditions.

II. OUTER PLANETS STUDIES

The basic configuration and technique for conducting the measurement of millimeter-wave absorptivity of gases under simulated conditions for planetary atmospheres is described at length in Semiannual Status Report #11 for Grant NAGW-533. As stated in the report, measurements of the absorptivity of gaseous ammonia under simulated Jovian conditions have been completed at both Ka-Band (32-40 GHz) and W-Band (94 GHz). In the last part of the grant year, we have completed the analysis of all laboratory data from these experiments.

We have compared our experimental data to various theoretical formulations for ammonia absorptivity. The Van Vleck-Weisskopf (1945) lineshape is known to be accurate at low pressures (less than 1 atm). Zhevakin and Naumov (1963) derived a different lineshape and found that their lineshape gave better results than the Van Vleck-Weisskopf theory when compared to experimental data for atmospheric water vapor absorption. This lineshape was also derived independently by Gross (1955) and is sometimes referred to as the kinetic lineshape. Ben-Reuven (1966) derived a more comprehensive lineshape which was found to be more accurate at higher pressures. Several modifications to the Ben-Reuven formalism (i.e. Morris and Parsons, 1970) have been made for applications in planetary science as more laboratory data under planetary conditions has become available. Recently, Spilker and Eshleman (1988) have derived new pressure and temperature dependences for the Ben-Reuven lineshape based on laboratory data under simulated Jovian conditions from high accuracy measurements at 9-18 GHz. Their formalism may be extrapolated to the frequencies and conditions of our experiments.

Figure 1 shows a graph of the four theoretical formulations which have been investigated for ammonia absorptivity from 1 to 1000 GHz (under the conditions of the Ka-Band experiment). These are labeled VVW for the Van Vleck-Weisskopf lineshape, BR-BG for the Berge and Gulkis (1976) formalism of the Ben-Reuven lineshape, BR-TS for the Spilker modified Ben-Reuven lineshape (private communication, 1988), and ZN-G for the Zhevakin-Naumov (1963) or Gross (1955) lineshape. The contribution from the rotational lines near 600 GHz has been included. All calculations employ center frequencies and line intensities given by Poynter and Kakar (1975). The two Ben-Reuven formalisms also include the modification by Morris and Parsons (1970).

Figure 2 shows the results of our Ka-Band experiment as compared to three of the theoretical lineshapes. The Spilker modified lineshape is not shown here, but is essentially the same as the Gross (Zhevakin-Naumov) shape for this frequency range (see Figure 1). Since the data favors both the Gross lineshape and the Spilker formalism at these frequencies, it is not clear which is more appropriate. However, by making measurements at a higher frequency where the lineshapes are more distinct, it is possible to determine which of these lineshapes is more appropriate. Figure 3 shows the results of our 94 GHz experiment as compared to all four theoretical lineshapes. At this frequency it is clear that neither the Van-Vleck Weisskopf lineshape nor the Gross lineshape is adequate in describing the observed opacity.

Because the Spilker formalism is based on laboratory data which was taken at pressures greater than 1 atm, we cannot assume that it is valid at lower pressures. In fact, this model contains a singularity around 1 atm. Theory predicts that there should be a smooth transition from the Ben-Reuven formalism to the Van Vleck-Weisskopf formalism at some low pressure. However, it is not known at what pressure this transition occurs. Although absorptivity measurements were initially made at several pressures ranging from 1 to 2 atm, the sensitivity of our measurement apparatus was not great enough to detect ammonia absorption under experimental conditions at pressures near 1 atm. In fact, no reliable data at Ka-Band (32-40 GHz) was taken below 2 atm. However, at W-Band (94 GHz), one reliable data set at pressures near 1 atm was available. Careful analysis of the data taken at a pressure of 1 atm shows that although no significant absorption was detected, the error bars reflect an upper limit for the opacity due to ammonia. This upper limit is well below the Van Vleck-Weisskopf theory even at 1 atm. This analysis is significant in that it shows the transition to the Van-Vleck Weisskopf theory must occur at some pressure

pressure below 1 atm.

Another activity over the past grant year has been the development of a radiative transfer model of the Jovian atmosphere. This model will utilize our laboratory data and can also be used to evaluate the need for further laboratory measurements of other possible absorbers. The model is similar to that described in dePater and Massie (1985), where a simple spherical model has been used instead of an oblate spheroid. The model is written in PASCAL and can be run on any IBM compatible personal computer. With appropriate modifications, it can also be used to model the other Jovian planets. At the present time, we have a working model which we have used to generate simulated emission spectra. Over the next several months, we plan to further improve the model so that we may evaluate the effects of various microwave and millimeter-wave absorbers.

The temperature-pressure profile for our Jovian model is shown in Figure 4, where we have tried to match the profile given by dePater and Massie (1985) as closely as possible. The dePater and Massie profile is based on Voyager data from Lindal et al. (1981) with an adiabatic extrapolation to the deeper levels of the atmosphere. We have also matched their ammonia abundance profile in order to see how our model compares with theirs. The ammonia abundance profile is shown in Figure 5. A sample output from our model is shown in Figure 6. This model utilizes the Ben Reuven (Berge and Gulkis, 1976) formalism for ammonia absorption. When all of the assumptions of dePater and Massie are matched, we find that our spherical model differs from their oblate spheroid model by less than 5K (less than 3%) at all wavelengths from 1 mm to 10 cm (3-300 GHz). This is certainly within the error bars of the actual radio observations at these wavelengths.

The next step will be to develop some kind of formulation for computing the absorption from ammonia at all temperatures, pressures, and frequencies based on all of the available laboratory data. Because laboratory data exists only at a few frequencies and at pressures above 1 atm, it is impossible to develop a single expression which will work under all conditions. The Spilker model provides a good estimate for the frequency dependence of the ammonia inversion spectrum under Jovian conditions at pressures around 2 atm. However, because of a singularity near 1 atm, it cannot be used in the model at all pressures. Instead of trying to use one single formulation for ammonia absorptivity which works at all temperatures, pressures, and frequencies, we will try a different approach. We will use the different theoretical and empirical formulations (i.e. those in Figure 1) over the entire frequency spectrum, but only at pressures and temperatures where they are known to be accurate. Since the abundance profile of ammonia contains abrupt changes at cloud layers, we may change the absorption spectrum at points in the model which will not cause severe discontinuities. For example, we may use either the Van Vleck-Weisskopf or the Ben-Reuven lineshape to describe ammonia absorption in the upper atmosphere above the main cloud layer (pressures below 0.7 atm.), where ammonia is depleted and the overall pressure is low. Since the contribution to the brightness temperature is negligable at these pressures, the assumed lineshape will not affect the calculated brightness temperature. The Berge and Gulkis formulation of the Ben-Reuven lineshape may be used from the main cloud layer to pressures above 1 atm. where the mixing ratio of ammonia levels off. The Spilker formalism may then be used at pressures above 1 atm., where it is known to be accurate.

We attempted to run our model using this approach. However, the Spilker formalism failed at higher frequencies for pressures greater than 1 atm. Further analysis of the Spilker formalism is needed before this lineshape can be used at higher frequencies and at pressures between 1 and 2 atm. We will continue to develop a model for ammonia absorption, based on laboratory results, which can be used in the emission model.

At the present time, the laboratory results can be used to give a lower limit for the abundance of ammonia on Jupiter. Since our laboratory results show that ammonia is <u>less</u> opaque than than the Ben-Reuven lineshape predicts, the models of brightness temperature produced using the Ben-Reuven lineshape give a <u>lower</u> limit for the predicted brightness temperature. In other words, model output using the laboratory data will give higher brightness temperatures than those using the Berge and Gulkis (1976) Ben-Reuven formalism. DePater and Massie (1985) showed than <u>more</u> opacity was needed in order to account for the cooler brightness temperatures observed at millimeter-wavelengths. Thus, our laboratory results show than more ammonia must be present or other absorbers must exist in order to explain the observations.

Figure 7 shows several weighting functions for our Jovian model using the Berge and Gulkis model for ammonia absorption. At the peak of the ammonia inversion spectrum at 23 GHz, the main contribution to the brightness temperature comes from the layers just below the high-altitude crystalline ammonia cloud layer. At 40 GHz (Ka-Band), the main contribution centers around 1 atm. The weighting functions for 10 GHz and 94 GHz are almost identical. Since laboratory data has shown that ammonia absorption is less than the Ben-Reuven lineshape predicts, and virtually the same at both of these frequencies, we would expect the brightness temperatures to be similar at both frequencies for a given ammonia profile in the Jovian atmosphere. However, the observed brightness temperatures given in dePater and Massie (1985) show that the observations near 94 GHz (3.2mm) are lower than those at 10 GHz (3 cm). This would seem to suggest an additional absorber at millimeter-wavelengths. Note however, that Klein (private communication) recently suggested that more uncertainty in the flux from calibrator stars used at millimeter-wavelengths may exist than previously thought, and that further study of the absolute emission from Jupiter may be necessary.

Bezard et al. (1983) have modelled the effects of hydrogen sulfide gas (H_2S) on the millimeter-wave spectrum of Jupiter. They have shown that hydrogen sulfide gas may be used to explain the cooler temperatures which have been observed at millimeter-wavelengths. We have developed our own model of hydrogen sulfide absorption based on line strengths given by Helminger (1972). The line widths and broadening parameters for this gas have never been measured and can only be estimated. Bezard et al. (1983) do not state the assumed linewidths employed in their calculations. We have used the broadening parameters for hydrogen and helium on water vapor as given by Goodman (1969) with a Van Vleck-Weisskopf lineshape in order to model the hydrogen sulfide absorption. However, as in the case of ammonia, the actual absorption at higher pressures may be significantly different from that calculated using the Van Vleck-Weisskopf theory. The calculated absorption from H_2S under Jovian condition for approximately ten times solar amount (4×10^{-4}) is shown in Figure 8. Analysis of this figure shows that by using higher concentrations of H_2S, absorption could be measured with our laboratory configuration.

Larson et al. (1984) have developed a profile for the vertical distribution of hydrogen sulfide for Jupiter. This profile is shown with the ammonia profile in Figure 5. An ammonium hydrosulfide cloud (NH_4SH) is proposed around 2 atm, above which H_2S is depleted and below which a solar abundance of H_2S exists. The model was run using this profile along with our formulation for hydrogen sulfide absorption. The model spectra with and without hydrogen sulfide absorption are shown in Figure 9. The hydrogen sulfide spectrum should be slightly smoothed as in Bezard et al. (1983). However, this does give an upper limit on the effect of adding this H_2S profile to the model. This profile is also a lower limit on the amount of H_2S which may be present in the atmosphere of Jupiter. Several researchers (e.g. Briggs and Sackett, 1989) have suggested that as much as ten times the solar amount of H_2S may be present on the Jovian planets. A third model emission spectrum resulting from an H_2S profile similar to that in Figure 5, but with ten times the solar abundance below the NH_4SH cloud is also shown in Figure 9. Note that at the H_2S line centers, the calculated brightness temperature is not dependent on the H_2S mixing ratio, but is dependent on the level at which the ammonium hydrosulfide cloud is placed. This is similar to the effect at the center of the ammonia inversion spectrum at 23 GHz, where the brightness temperature is dependent on the level of the ammonia cloud layer as shown by the weighting function in Figure 7.

Over the next several months, we plan to further investigate the effects of different H_2S and NH_3 abundance and absorption profiles on the calculated emission spectra. We will also investigate the possible effects of cloud condensates on the millimeter-wave emission. We will then evaluate the need for laboratory measurements of gaseous H_2S and other possible liquid absorbers.

III VENUS STUDIES

The laboratory measurement of the dissociation factor of gaseous H_2SO_4 in equilibrium with liquid sulfuric acid is desperately needed in order to allow proper interpretation of both future and existing work on the opacity of gaseous H_2SO_4 and to properly model its saturation abundance in the Venus atmosphere. Steffes (1985,1986), estimated that about 47% of the gaseous H_2SO_4 which vaporized from a liquid sulfuric acid reservoir, dissociated to form gaseous SO_3 and H_2O. Using this assumption, Steffes proceeded to calculate the mixing-ratio normalized opacity of gaseous H_2SO_4, which is believed to be the major predominant microwave absorber at altitudes above 30 Km in the Venus atmosphere. The laboratory measurements used for calculating the normalized opacity were conducted at wavelength ranging from 1.3 to 22 cm. One wavelength of major interest is 13 cm. Its importance is due to the fact that measurements of localized absorptivity at that frequency have been provided by the Pioneer-Venus Orbiter Radio Occultation (ORO) experiment.

A. EXPERIMENTAL SETUP

The measurements are conducted using the apparatus shown in Figure 10. In this setup, a large vacuum chamber (of known volume), is constructed using Pyrex glass as shown in Figure 11. The reason for choosing Pyrex is its ability to withstand high temperatures (600 K). The top of the glass chamber was sealed using a stainless steel plate. A high temperature O-ring was sandwiched between the glass and the plate to insure that leaks are minimal at that junction. A special purpose clamp is used to hold the plate to the glass lip. Stainless steel pipes and valves are used throughout the system in order to minimize acid-metal reaction at high temperatures. The pipes were submerged in sulfuric acid solution to dissolve surface impurities. The flask is also constructed of Pyrex glass. Another reason for choosing glass is the ability to monitor the status of the sulfuric acid vapor, and to make sure that no vapor condensation is occurring during pressure measurement.

The chamber and the flask had to be fitted inside a temperature controlled oven. The temperature inside the oven is monitored using a pre-calibrated thermocouple. The output of the thermocouple is connected to a digital voltmeter, the temperature is then inferred using voltage versus temperature data of the thermocouple. Two vacuum gauges are used in the experiment. Gauge P1 is used to monitor the status of the chamber, i.e. checks for leaks. The range on P1 is 0 - 20 Torr. Gauge P2 is connected to a digital pressure display. The gauge is able to measure pressures ranging from 0 to 800 Torr in 1 Torr increments, with accuracy of $\pm$ 1 Torr throughout its usable range. The latter gauge is used to measure total pressure in the chamber at the desired temperature. A nitrogen buffer is used in the setup so as not to allow any sulfuric acid vapor to come in contact with gauge P2. The buffer is filled with a predetermined amount of nitrogen. No buffer is necessary for gauge P1 because the valve is closed during pressure measurements. The experiment is conducted at six distinct temperature points ranging from 490 to 600 K. Two different concentrations of liquid sulfuric acid are used, 99% and 95.9%. Acid samples were provided by the Du Pont Company. The flask is filled with a precisely known volume of liquid sulfuric acid at room temperature. The volume measurements are made using a 1-ml syringe with 0.01 ml gradations. For volumes less than 1 ml, repeatable accuracies of better than .01 ml have been obtained.

The apparatus is first heated to the desired temperature (usually taking about four hours). At that point, a vacuum is drawn. Using gauge P1 we are able to make sure that leaks are minimal, since any major leak can affect the total measured pressure, therefore altering the dissociation constant. Our system had a leak rate of approximately 1 Torr/hour. The system is allowed to reach thermal equilibrium, by continuously monitoring the temperature. The flask valve is then opened allowing the liquid H_2SO_4 to reach vapor pressure equilibrium with the evacuated chamber. Once equilibrium is reached, the valve is closed, and a check is made to verify that the remaining liquid is clear. The valve is usually opened for a period of ten minutes. The buffer is then opened and the chamber pressure is recorded. It is important to emphasize that throughout this process the temperature had to be within certain limits of the desired value, thus allowing the temperature variation factor to be minimal. In this case we were able to maintain oven temperature to within $\pm$ 5 K. The system is then allowed to cool overnight to its original room temperature. The remaining volume of liquid sulfuric acid is measured and the evaporated volume is inferred.

B. RELATION BETWEEN MEASURED QUANTITIES AND RESULTS

Let V_{Liquid} (ml) denote the volume of liquid H_2SO_4 and liquid H_2O which evaporates from the flask in Figure 10.

$$V_{Liquid} = V_{H_2SO_4} + V_{H_2O} \tag{1}$$

The percent concentration of the liquid sulfuric acid (by mass) is defined as follows : (i.e. PCM = .99 for 99% concentration by mass)

$$PCM = \frac{V_{H_2SO_4} \quad \rho_{H_2SO_4}}{V_{H_2SO_4} \quad \rho_{H_2SO_4} + \quad V_{H_2O}\,\rho_{H_2O}} \tag{2}$$

where ρ_{H_2O} = density of H_2O (1 gm/ml). From equation (1) and (2) one can solve for V_{H_2O} and $V_{H_2SO_4}$:

$$V_{H_2O} = \frac{V_{H_2SO_4}\,\rho_{H_2SO_4}\,(1-PCM)}{PCM} \tag{3}$$

and

$$V_{H_2SO_4} = \frac{V_{Liquid} \cdot PCM}{PCM + \rho_{H_2SO_4}\,(1-PCM)} \tag{4}$$

In equations (3) and (4), the density of liquid H_2O have been assumed to be 1 gm/ml. Given the density of liquid sulfuric acid (gm/ml), it is possible to compute the number of H_2SO_4 molecules which are converted to vapor phase by the relation :

$$n_{vapor} = (V_{H_2SO_4} \cdot \rho_{H_2SO_4})/98 + (V_{H_2O} \cdot \rho_{H_2O})/16 \qquad (5)$$

where n_{vapor} is the number of molecules (in moles) which vaporized during the experiment. The total number of molecules in the chamber (n_{total}) which resulted from the vaporized molecules can be determined assuming a dissociation factor D:

$$n_{Total} = \left[\frac{V_{H_2SO_4} \cdot \rho_{H_2SO_4}}{98} \right] (1+D) + \left[\frac{V_{H_2O} \cdot \rho_{H_2O}}{16} \right] \qquad (6)$$

where D is the portion of H_2SO_4 molecules which dissociate to form SO_3 and H_2O. (The range of D is between 0 and 1). The pressure P (Atm) obtained from the evaporated liquid sulfuric acid can be directly measured during the experiment. P is related to n_{total} by the ideal gas equation :

$$P \, V_{Chamber} = n_{Total} \cdot R \cdot T \qquad (7)$$

$V_{chamber}$ (l) is the volume of the chamber occupied by the evaporated gas. R is the ideal gas constant (.08205 l.Atm/mole.K), and T is the temperature of the chamber in Kelvins (K). Combining the above equations, and solving for the dissociation constant D yields :

$$D = \frac{784 \cdot PCM \cdot P \cdot V_{Chamber} + V_{H_2SO_4} \cdot \rho_{H_2SO_4} \cdot R \cdot T \cdot (41\ PCM - 49)}{8\ (PCM)\ V_{H_2SO_4} \cdot \rho_{H_2SO_4} \cdot R \cdot T} \tag{8}$$

Thus if the chamber volume, temperature of the system, density of sulfuric acid, pressure resulting from the evaporated liquid acid, and the amount of evaporated liquid are known, by using equation (8) one can compute the dissociation factor D.

Another important derivation is the calculation of the partial pressure of sulfuric acid ($P_{H_2SO_4}$ (Atm)). The calculation of the partial pressure, will enable us to go back and correct the measured normalized microwave absorptivity (Steffes, 1985) for gaseous H_2SO_4 in a CO_2 atmosphere at 13.4 and 3.6 cm. wavelength. The total pressure P can be written as :

$$P = P_{H_2O} + P_{SO_3} + P_{H_2SO_4} \tag{9}$$

Since $P_{H_2O} = P_{SO_3}$, (9) becomes :

$$P = P_{H_2SO_4} + 2\ P_{SO_3} = P_{H_2SO_4} + 2\ P_{H_2O} \tag{10}$$

The dissociation factor D can also be written as :

$$D = \frac{P_{SO_3}}{P_{H_2SO_4} + P_{SO_3}} \tag{11}$$

Combining (10) and (11) yield :

$$P_{H_2SO_4} = P \cdot \frac{1 - D}{1 + D} \tag{12}$$

Thus the partial pressure of sulfuric acid can be computed from the knowledge of the total pressure measured and the calculated dissociation factor D using (8). Note that when the dissociation factor is unity (10) and (12) yield :

$$P = 2\ P_{SO_3} = 2\ P_{H_2O} \tag{13}$$

Knowing the volume of the evaporated liquid and the pressure in the chamber the dissociation factor D can be calculated. Using D, the partial pressure of gaseous sulfuric acid can then be calculated using (12).

C. RESULTS

Figure 12 is a plot of the calculated partial pressure of gaseous sulfuric acid above liquid sulfuric acid as a function of temperature for a 99% (by weight) concentration. Illustrated points are from laboratory measurements. The solid line is the partial pressure of sulfuric acid as calculated by Steffes (1985). Dashed line is a best-fit curve to the lab measurements. The temperature dependence of the vapor pressure of gaseous sulfuric acid is given by :

$$n\ p = 2.72 - 3952/T \tag{14}$$

where p is the sulfuric acid vapor pressure in atmospheres and T is the temperature in Kelvins. A similar result is obtained for a 95.9% concentration as shown in Figure 13. Its best-fit expression is given by (15):

$$n\ p = 2.89 - 4132/T \tag{15}$$

Figure 14 compares the best-fit results from these measurements with those obtained by Steffes (1985). Examination of our results indicate that the dissociation factor increases as the concentration is decreased. This is to be expected, since lower concentration means less sulfuric acid vapor pressure. Notice that the slope is constant for both concentrations, which suggests that partial pressure is proportional to concentration. Thus as concentration of sulfuric acid decreases so does the vapor pressure. Our results indicate that Steffes (1985) overestimated partial pressure at higher temperatures, and underestimated partial pressure at lower temperatures.

Although the above results are very critical in interpreting future and present work on the opacity of gaseous sulfuric acid, we need to further study the partial pressure of H_2SO_4 at lower temperatures. Thus, our results in this present form cannot currently be extrapolated to lower temperatures. The results from lower temperatures studies will allow us to develop a single expression for partial pressure of gaseious H_2SO_4 over a larger temperature range. In the next grant year, we will go back to the results obtained by Steffes (1985) and correct the normalized microwave absorptivity of gaseous sulfuric acid at 13.4 and 3.6 cm, in order obtain new sulfuric acid mixing ratio profiles for the Venus atmosphere. Our results can also be used to infer the saturated sulfuric acid abundance by using published data on the pressure-temperature dependence of the Venus atmosphere (Seiff et.al, 1980) along with our results. Since total pressure is known and saturated partial pressure can be calculated using our formulas, mixing ratio is then easily calculated.

IV. PUBLICATIONS AND INTERACTION WITH OTHER INVESTIGATORS

Over this past grant year, a paper was published in Icarus, describing results and applications of the laboratory measurements of the millimeter-wave opacity of ammonia between 7.5 and 9.38 mm, described in previous reports (Joiner et al., 1989). In addition, we completed a paper describing observations and interpretive studies of the 1.3 to 3.6 cm Venus emission spectrum (Steffes et al., 1989), which was also accepted for publication in Icarus. We also submitted updated summaries of our most recent laboratory measurements for inclusion in the twenty-third issue of the Newsletter of Laboratory Spectroscopy for Planetary Science.

We will attend the 21st Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society the week of October 30 through November 4, 1989. We will present 4 papers (abstracts attached--see Appendix A.) Three of these papers will address laboratory measurements and interpretive studies of the Venus atmosphere, and one will present results of millimeter-wave studies of the Jovian atmosphere.

In addition to the radio astronomical observations of Venus and analysis work conducted jointly with Dr. Michael J. Klein of JPL, we have also worked with Dr. Michael A. Janssen of JPL regarding models for the Venus atmosphere and the outer planets, interpretation of microwave emission measurements, and theoretical models for the absorption spectrum of H_2SO_4. We have also worked with Dr. Arvydas J. Kliore of JPL on the reduction and interpretation of data from recent Pioneer-Venus Radio Occultation Studies as part of our involvement in the Pioneer-Venus Guest Investigator Program. More informal contacts have been maintained with groups at the California Institute of Technology (Drs. Duane O. Muhleman, Kathryn Pierce, and Arie Grossman, regarding interpretation of radio astronomical measurements of Venus and the outer planets). We have also worked closely with the Stanford Center for Radar Astronomy (Drs. V.R. Eshleman, G.L. Tyler, and T. Spilker, regarding Voyager results for the outer planets, and laboratory measurements), and at JPL (Drs. Robert Poynter and Samuel Gulkis, regarding radio astronomical observations of the outer planets and Venus). We have also worked with Dr. Imke de Pater (University of California-Berkeley) by using out laboratory measurements of atmospheric gases in the interpretation of radio astronomical observation of Venus and the outer planets. We have also studied possible effects of the microwave opacity of cloud layers in the outer planets' atmospheres. In this area, we have worked both with Dr. de Pater and with Dr. Paul Romani (Goddard SFC).

During the Voyager-Neptune encounter, we supported the Voyager Radio Science Team by providing calculations of the expected atmospheric absorption by gaseous H_2S and NH_3 in the Neptune atmosphere, at the Voyager S-Band and X-Band downlink frequencies. These calculations were used both for pre-encounter operational planning and post-encounter interpretive studies.

Dr. Steffes has also been active in the review of proposals submitted to the Planetary Atmospheres Program at NASA (both as a "by-mail" reviewer and as a member of the February 1989 review panel) and as a reviewer of manuscripts submitted to Icarus, the Journal of Geophysical Research, Physics Reports, and Annual Review of Astronomy and Astrophysics. We have also continued to serve the planetary community through the distribution of reprints of our articles describing our laboratory measurements and their application to microwave and millimeter-wave data from planetary atmospheres. The results of these measurements have been used in the mission planning for radio and radar systems aboard the Galileo and Magellan missions, and more recently, for proposed experiments for the Cassini mission. Dr. Steffes also participated as a member of the International Jupiter Watch (IJW) Laboratory/Theory Discipline Team. Another source of close interaction with other planetary atmospheres principal investigators has been Dr. Steffes' membership in the Planetary Atmospheres Management and Operations Working Group (PAMOWG). Travel support for Dr. Steffes' attendance at PAMOWG meetings, as well as the November AAS/DPS meeting, has been provided by Georgia Tech in support of Planetary Atmospheres Research. Also, in support of Planetary Atmospheres Research, Georgia Tech has provided a Hewlett-Packard Vectra QS-16 Computing System.

As in the past, we have maintained contact with members of the Georgia congressional delegation, keeping them aware of our work and aware of our continued support for the solar system exploration program. We were especially pleased with the support received from Senator Wyche Fowler for the CRAF/Cassini "new start," after briefing his staff on this issue. (See Appendix B)

V. CONCLUSION

Over the past grant year, we have continued our work with laboratory measurements and interpretation of the millimeter-wave properties of atmospheric gases contained in the outer planets. The results of our studies have been significant in that they indicate that the large opacities predicted by a number of workers at these wavelengths are indeed incorrect and that a form of the modified Ben-Reuven formalism for computing the millimeter-wave opacity from ammonia is correct. In the future, we plan to continue development of our models for Jovian millimeter-wave emission. We plan to further investigate the effects of the H_2S and NH_3 on the calculated emission spectra. We will also evaluate the need for laboratory measurements of gaseous H_2S and other possible liquid absorbers.

Our Venus studies over the past grant year have made it possible for us to measure the dissociation of gaseous H_2SO_4 into SO_3 and H_2O, which will aid in modeling of the Venus atmosphere, and will make it possible to correct previous laboratory measurements of the microwave opacity of gaseous H_2SO_4. In the next grant year we intend to develop corrected expressions for the microwave opacity from gaseous H_2SO_4 which will allow a more accurate interpretation of the 13 cm absorptivity profiles provided by Pioneer-Venus radio occultation studies. We will likewise complete designs and begin laboratory measurement of the millimeter-wave properties of liquid H_2SO_4.

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VII. Key Figures

Figure 1: Theoretically calculated absorption from NH_3 under Jovian conditions using the Van Vleck-Weisskopf, Ben Reuven (Berge and Gulkis , and Spilker and Eshleman formalisms) and Zhevakin and Naumov or Gross lineshapes.

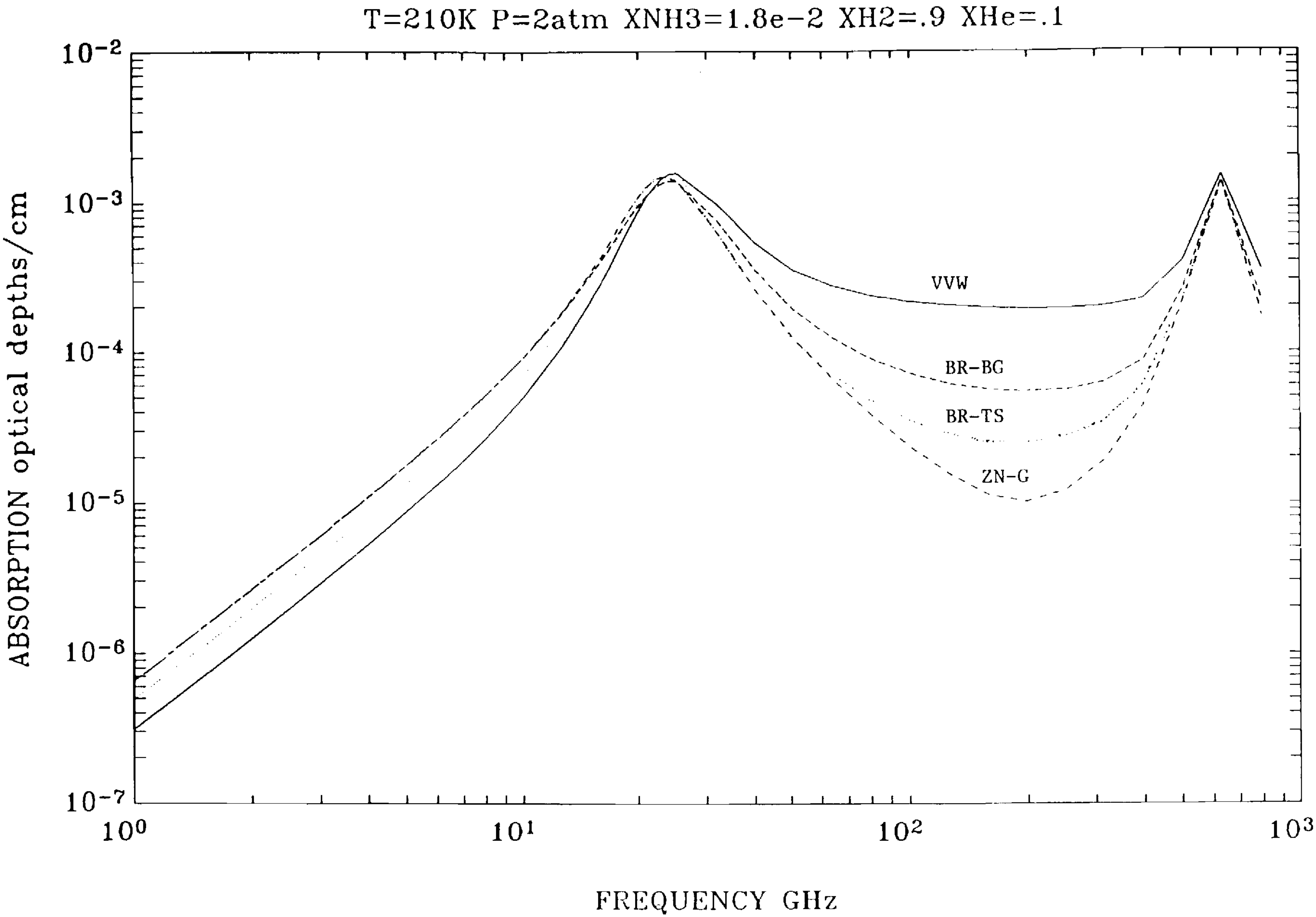


Figure 2: Absorption of NH_3 in a 88.34% H_2, 9.81% He, 1.85% NH_3 mixture (Mixing ratio: 0.0185±0.0005) Pressure: 2 atm. Temp: 203K

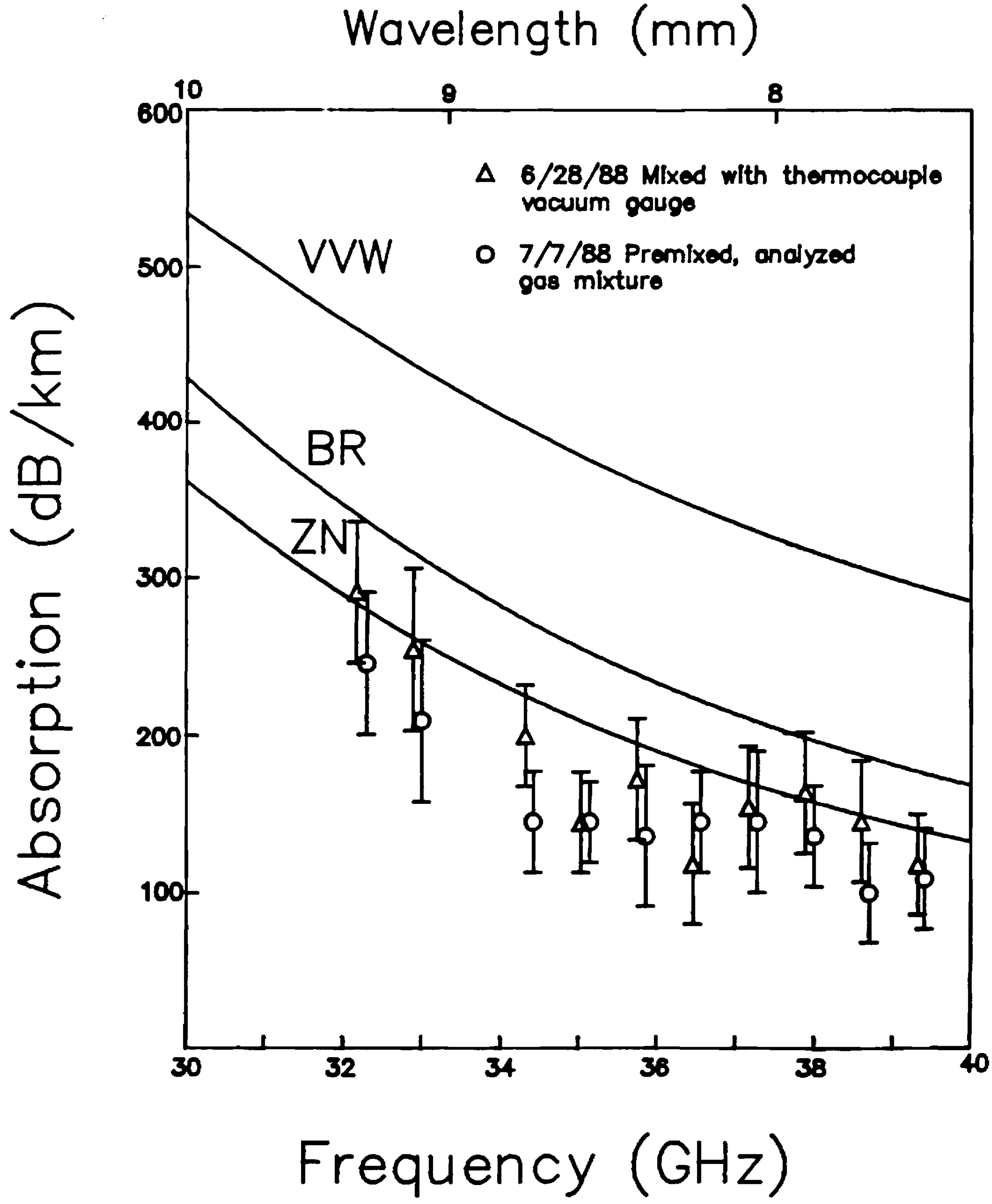


Figure 3: Measured ammonia (NH_3) absorption under Jovian conditions as compared to theoretically computed absorption.

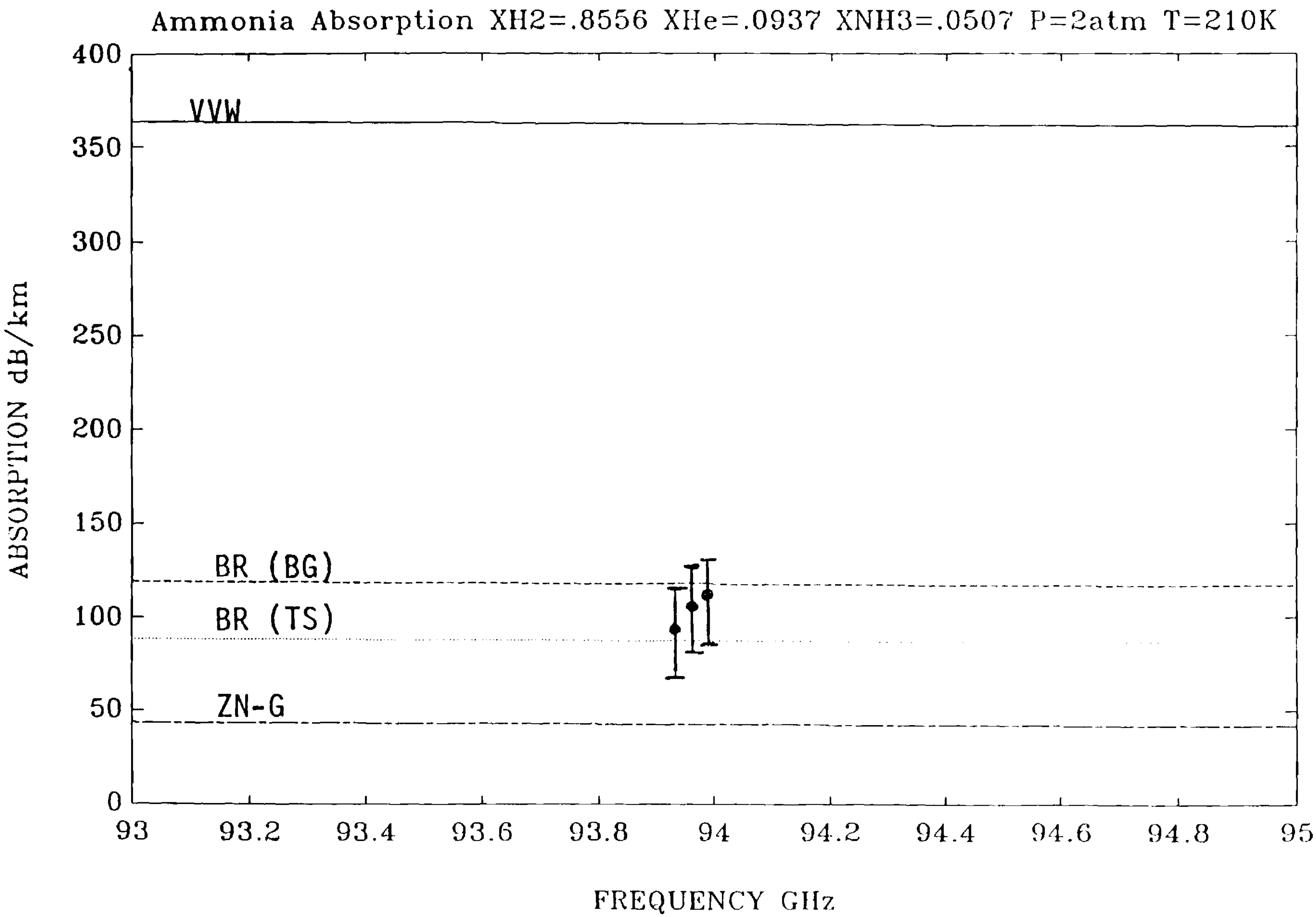


Figure 4: Jovian Temperature Pressure Profile (based on dePater & Massie)

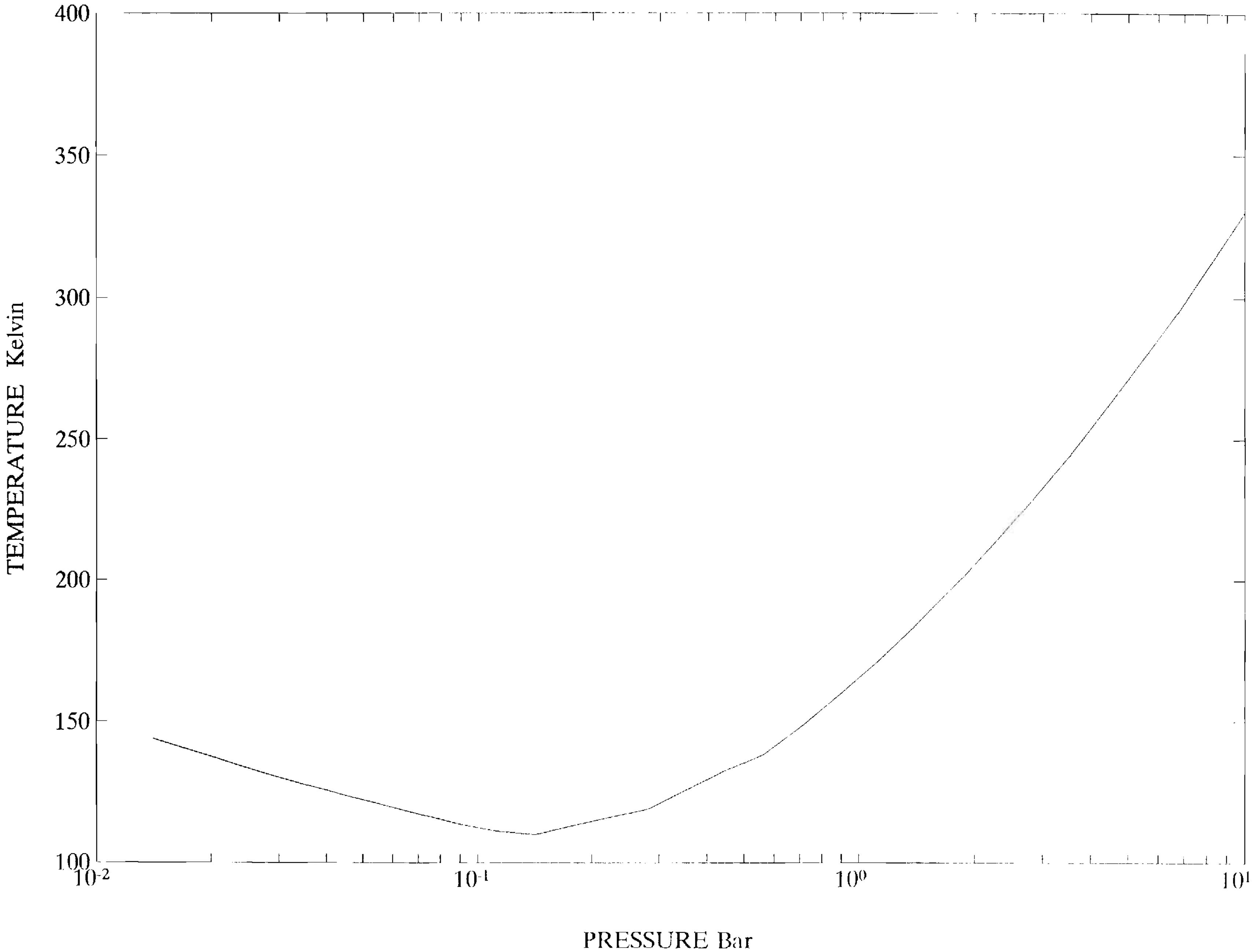


Figure 5: NH3 and H2S Mixing Ratios in Jovian Model

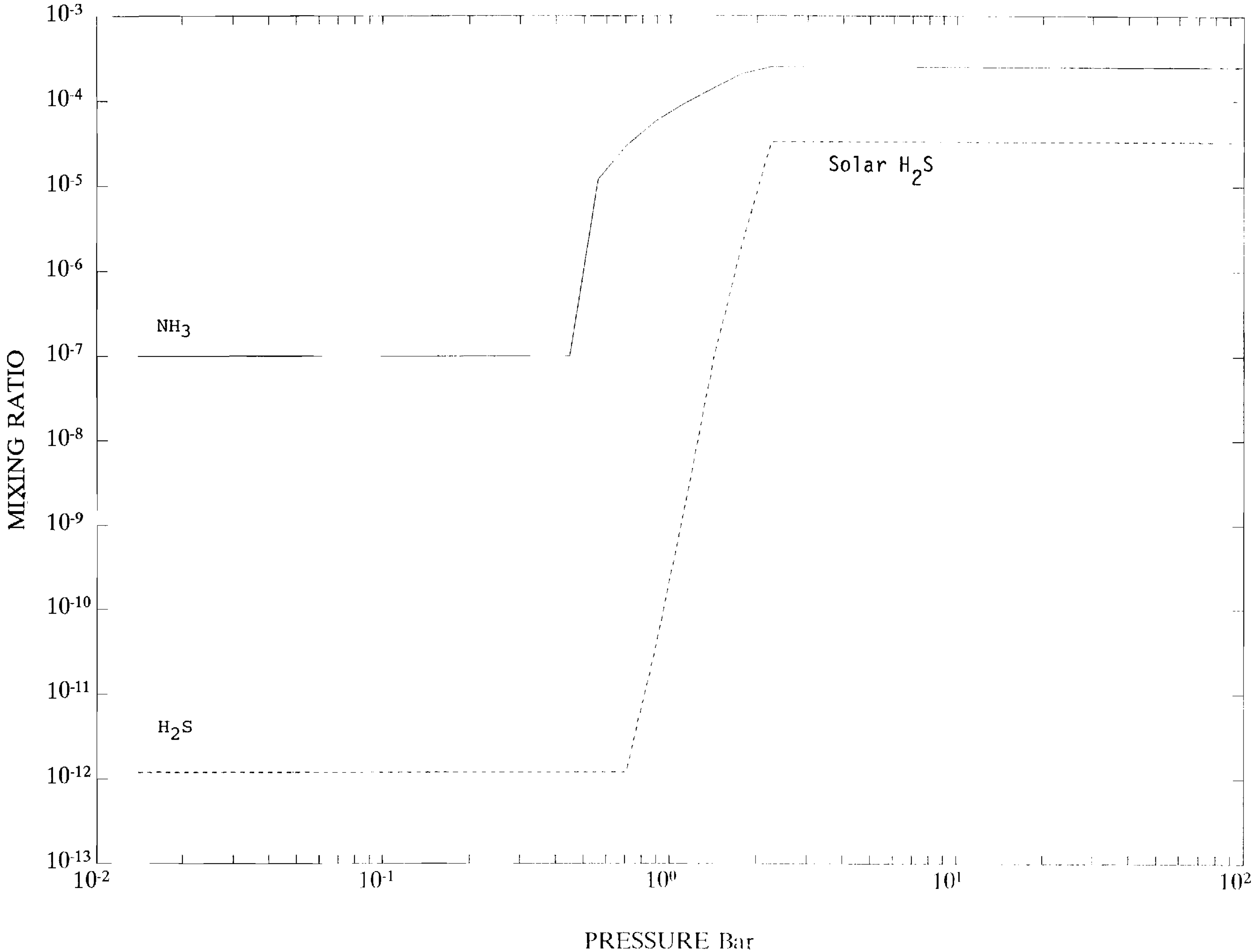


Figure 6: Jovian Model based on dePater & Massie 4BR NH_3 abundance as in Figure 5

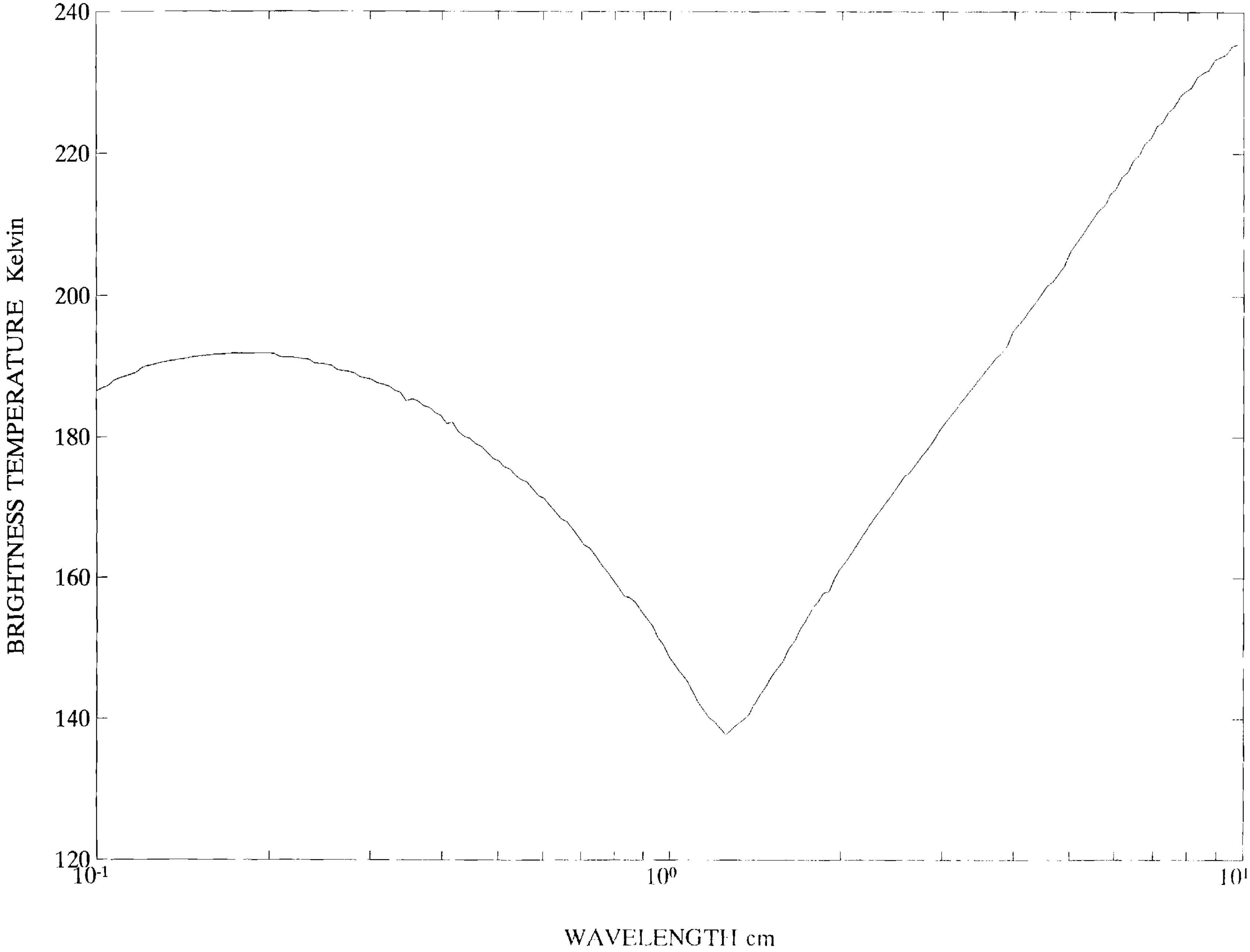


Figure 7: Weighting Functions for Jovian Model

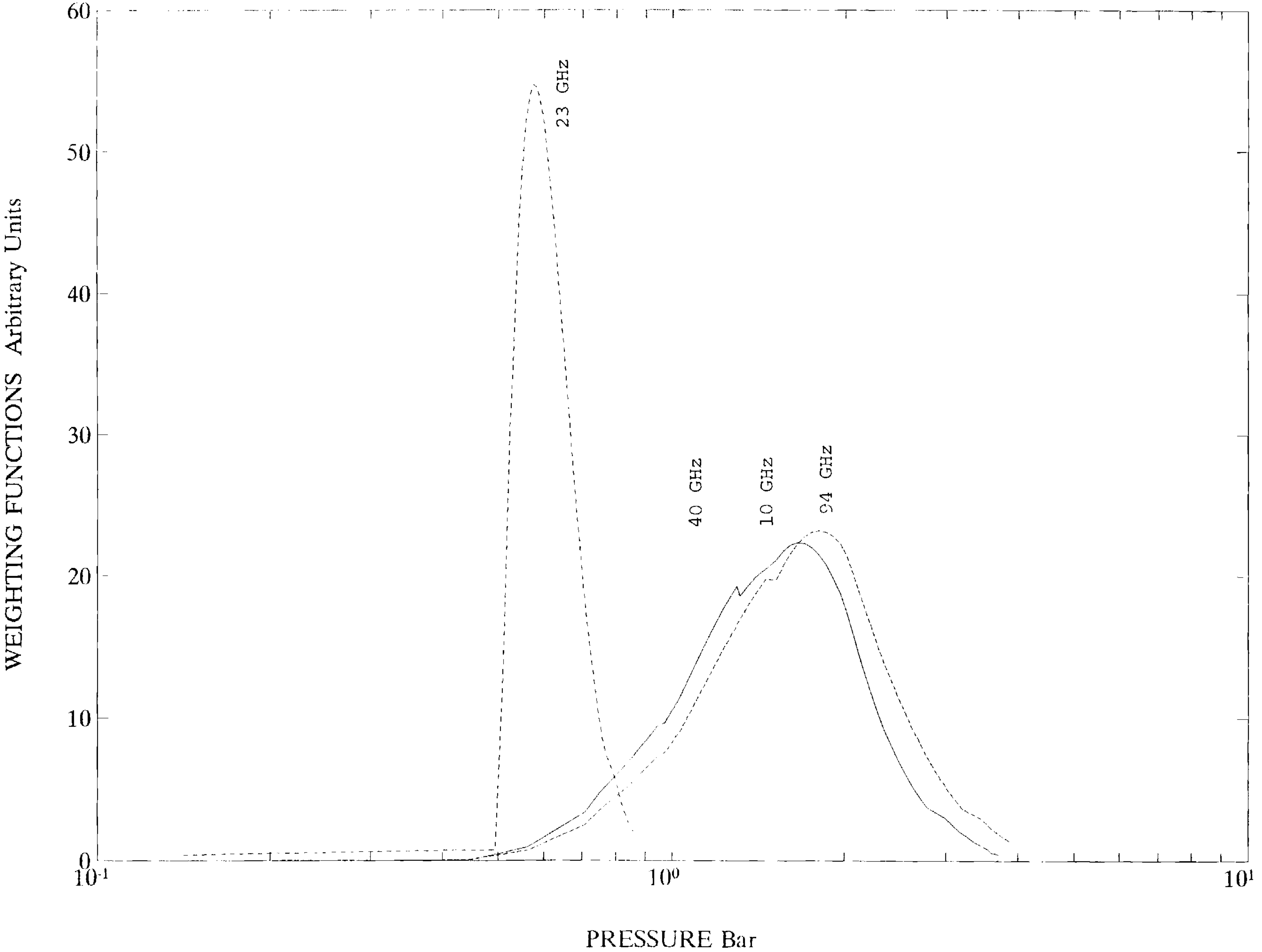


Figure 8: H2S Absorption XH2S=4e-4 XH2=.9 XHe=.1 T=200K P=2 atm (10X Solar H_2S)

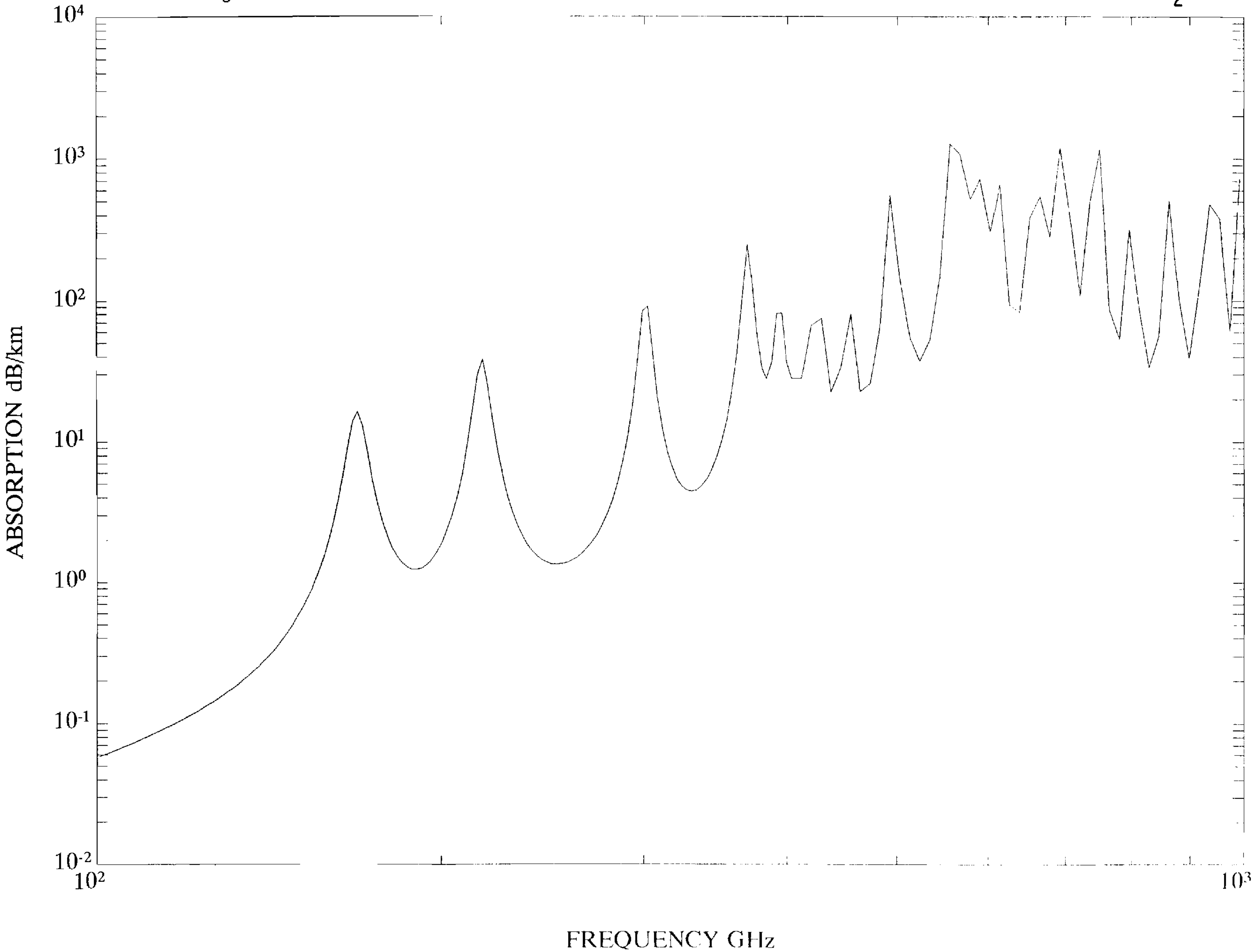
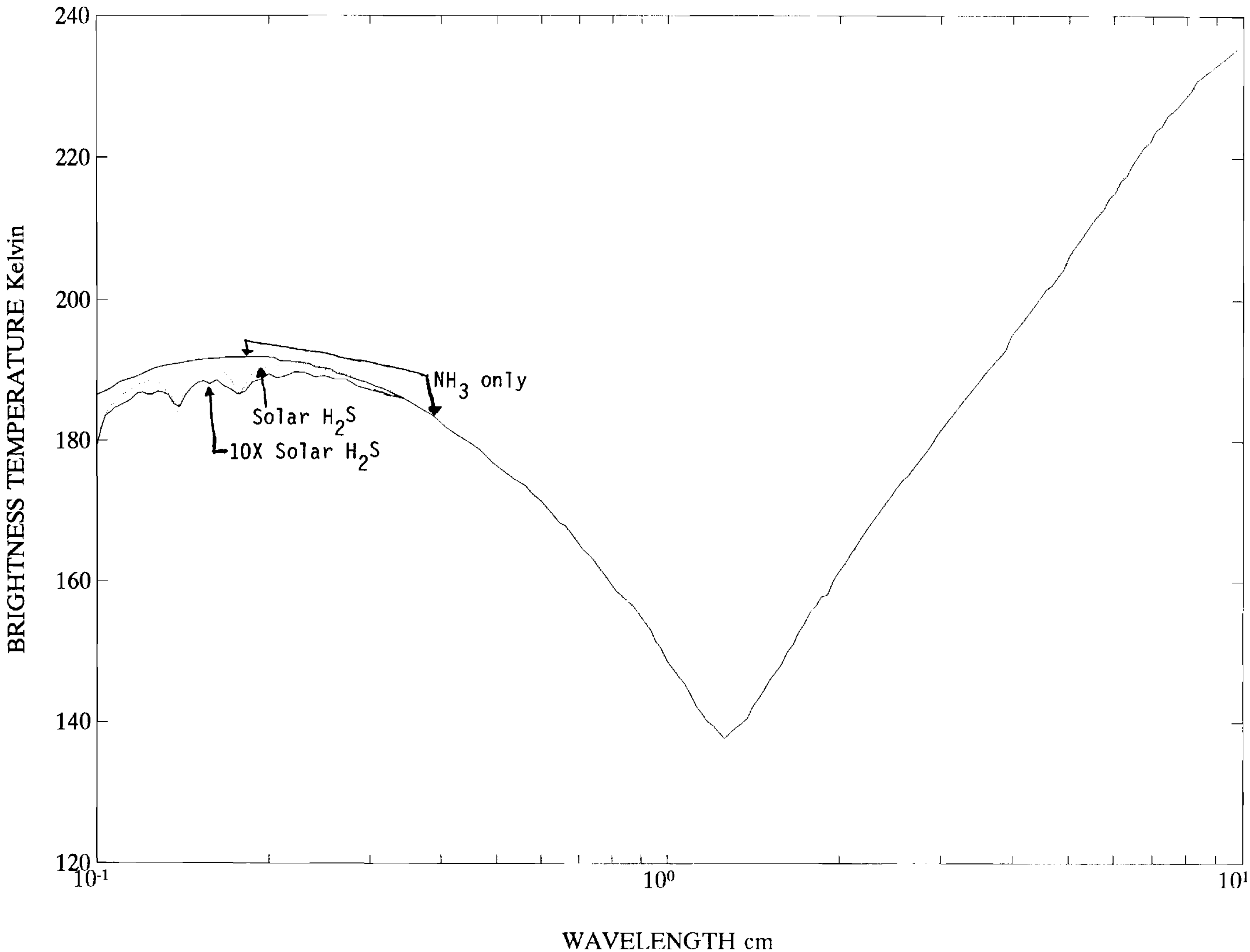


Figure 9: Jovian model with 1X and 10X Solar H2S and no H2S ammonia abundance as shown in Figure 5



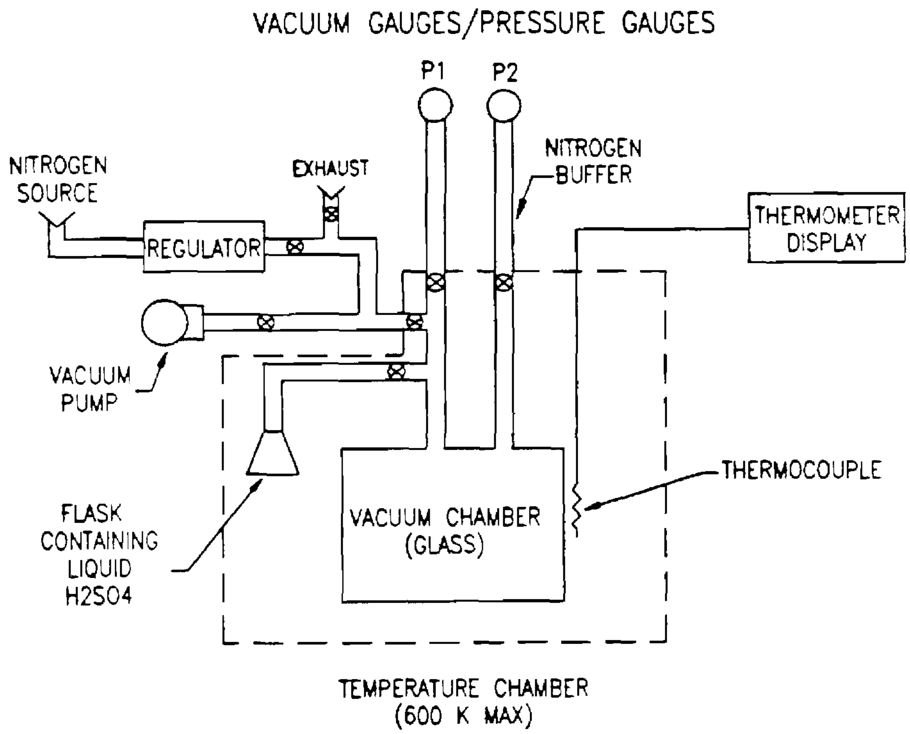


Figure # 10 : Laboratory apparatus used to measure the dissociation factor D, for H_2SO_4 above liquid sulfuric acid .

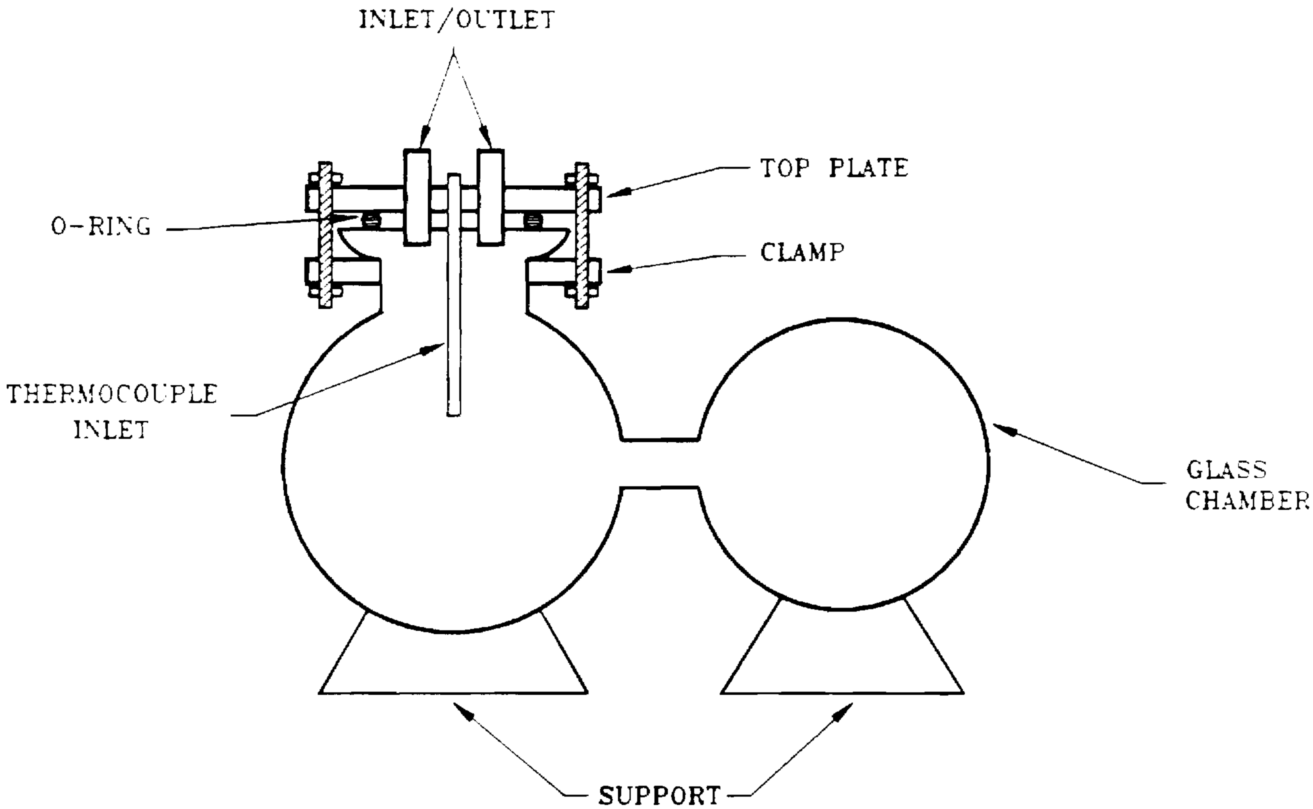


Figure # 11 : Cross section view of the vacuum chamber used in our apparatus .

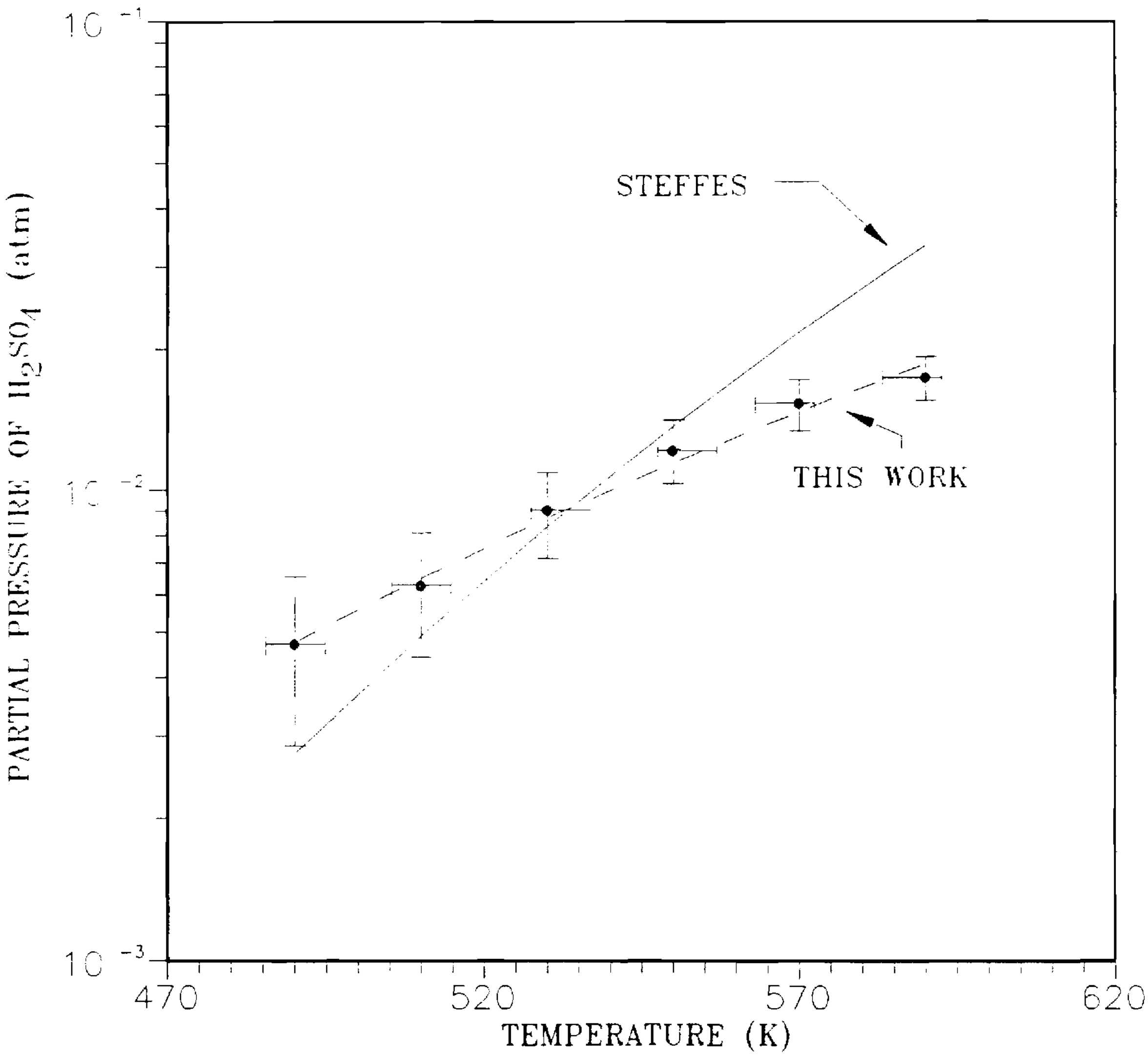


Figure # 12 : Vapor pressure of gaseous H_2SO_4 (99%) above liquid sulfuric acid as a function of temperature. The illustrated points are from laboratory measurements. Vapor pressure expression (solid line) from Steffes (1985) is compared with a best-fit expression for our measurements (dotted line). Error bars for pressure and temperature are shown.

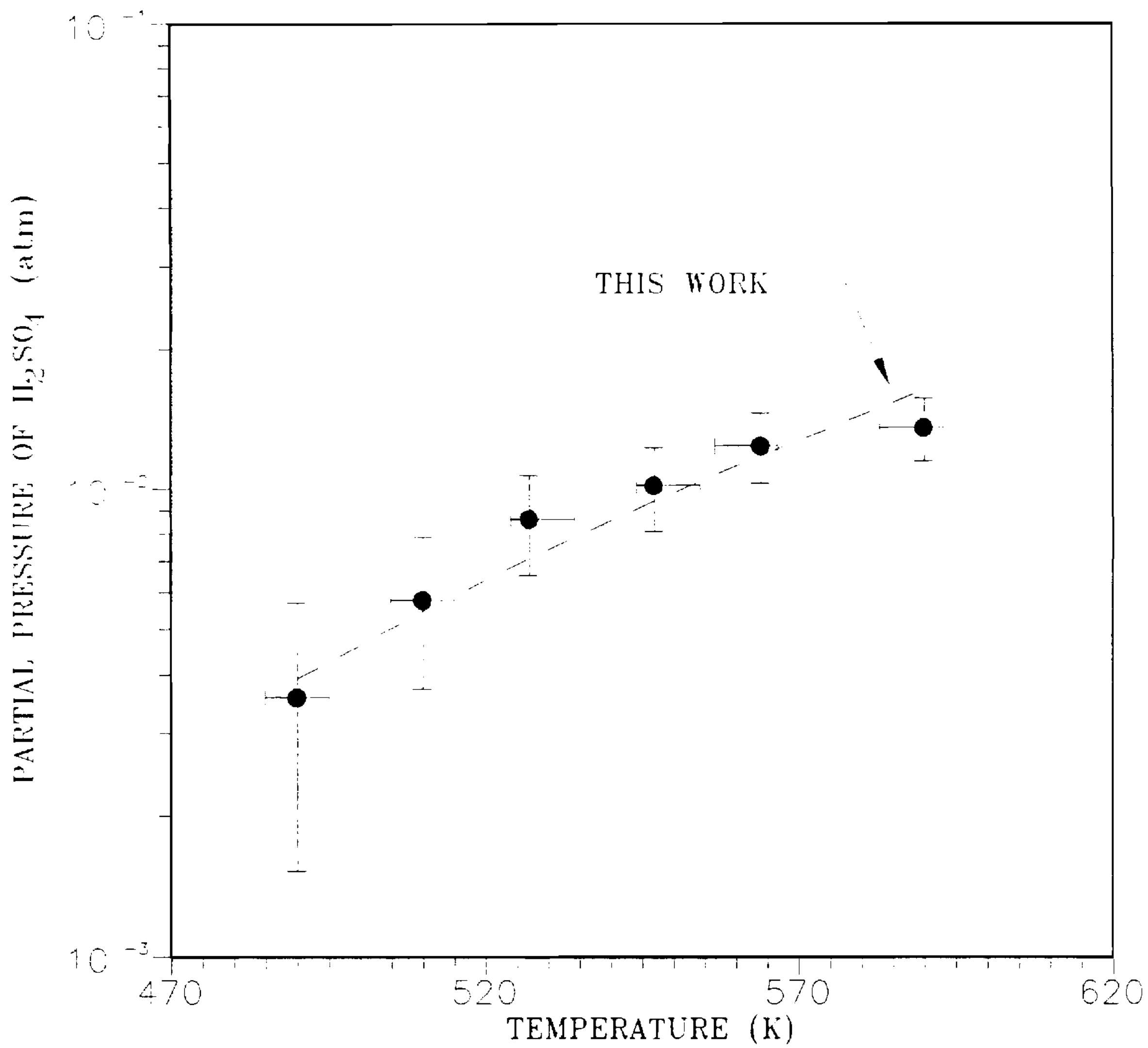


Figure # 13 : Vapor pressure of gaseous H_2SO_4 (95.9%) above liquid sulfuric acid as a function of temperature. Illustrated points are from laboratory measurements. Dotted line is a best-fit expression for our measurements. Error bars for pressure and temperature are shown.

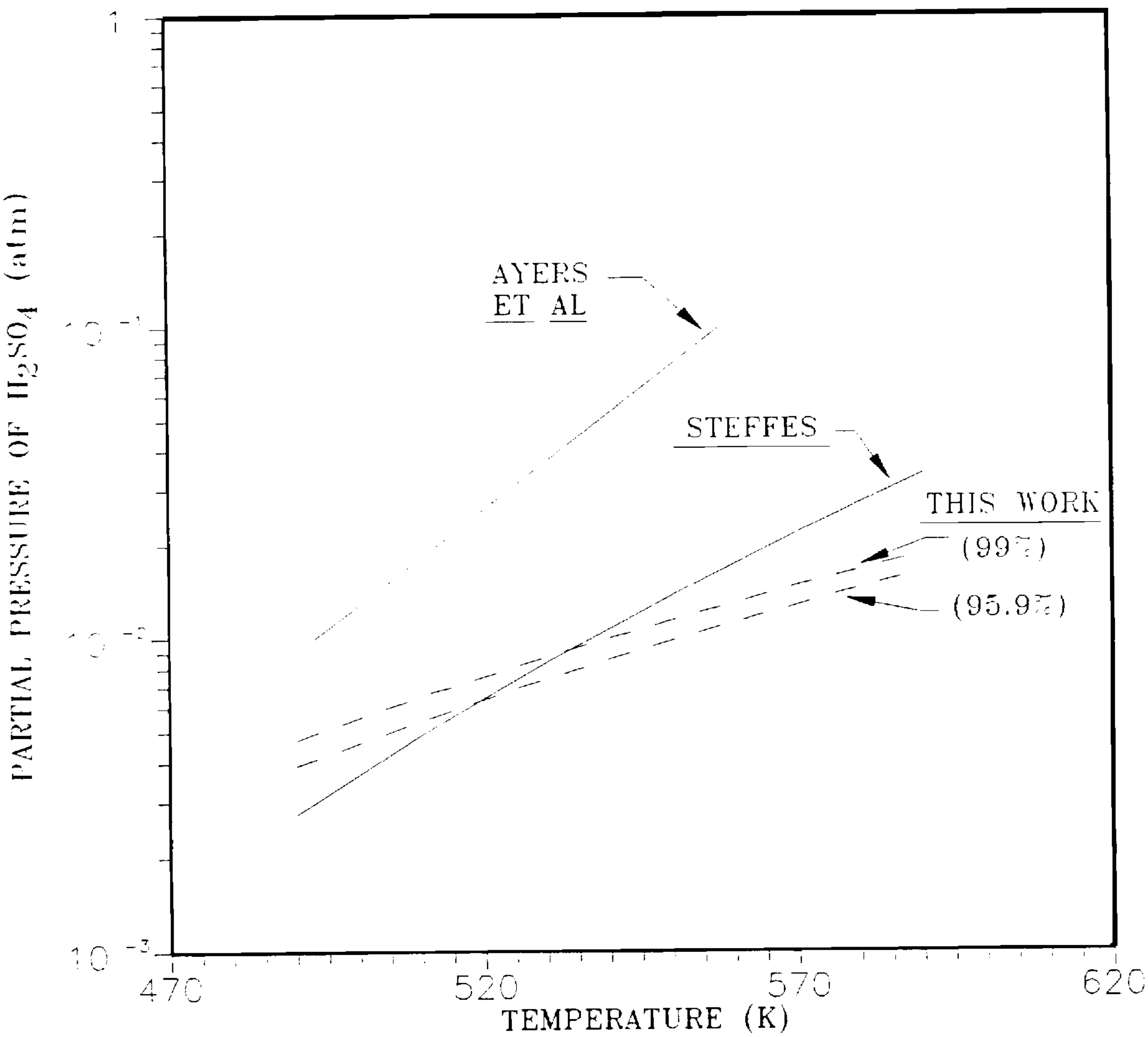


Figure # 14 : Best-fit expression (dotted line) for our measured partial pressure of H_2SO_4 as a function of temperature in comparison with vapor pressure expressions from Ayers et. al. (1980) and Steffes (1985).

Bull. Amer. Astron. Soc. 1989 p. 927

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Laboratory measurements of the dissociation factor of gaseous sulfuric acid (H_2SO_4)

A.K. Fahd, P.G. Steffes (Georgia Institute of Technology)

A good understanding of the dissociation of gaseous H_2SO_4 into SO_3 and H_2O is desperately needed in order to properly interpret laboratory measurements of the opacity of H_2SO_4. The dissociation factor is also valuable in order to accurately model the saturation abundance of gaseous H_2SO_4, SO_3, and H_2O in the atmosphere of Venus.

Laboratory measurements of the dissociation factor of sulfuric acid vapor are described. The experiment is being conducted at temperatures ranging from 480 to 580 K. Two concentrations of sulfuric acid have been used, (98.7%, 99.0%). The partial pressures of water, sulfuric acid, and sulfur trioxide can be inferred from the measurements. A comparison between our results and those calculated by Gmitro and Vermulen (1964, Amer. Inst. Chem. Eng. 10, 740-746) will be presented.

*This work was supported by the Planetary Atmospheres Program of the National Aeronautics and Space Administration under grant NAGW-533.

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 Bull. Amer. Astron. Soc. 1989 p.925

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Potential Variability of the Abundance and Distribution of Gaseous Sulfuric Acid Vapor Below the Main Cloud Deck in the Venus Atmosphere.

J.M. Jenkins, P.G. Steffes (Georgia Institute of Technology)

Studies of recent measurements of the 1.35 to 3.6 cm emission from Venus have suggested that long term temporal and/or spatial variations in the abundance of gaseous sulfuric acid vapor (H_2SO_4) may occur immediately below the main cloud layer (48 km and below). To investigate these issues, we have derived 13 cm absorptivity profiles from Pioneer-Venus Orbiter radio occultation data obtained in 1986 and 1987. Data from selected orbits have been analyzed which span a range of latitudes from 11°N to 88°N, solar zenith angles from 66° to 160°, and probe altitudes as deep as 40 km. In addition, upper limits on the abundance profiles of gaseous sulfuric acid vapor have been inferred from the absorptivity profiles. Furthermore, we have begun characterizing the uncertainties inherent in the data inversion process. When carried to its full potential, this radio occultation data will provide insight into possible variations in the abundance and distribution of gaseous H_2SO_4 below the main cloud layer in the Venus atmosphere.

*This work was supported by NASA Grant NAG 2-515. This material is also based on work supported under a National Science Foundation Graduate Fellowship.

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DIVISION FOR PLANETARY SCIENCES ABSTRACT FORM

Models of the Millimeter-Wave Emission of the Jovian Atmosphere Utilizing Laboratory Measurements of Gaseous Ammonia (NH_3)

J. Joiner, P.G. Steffes (Georgia Institute of Technology)

Radiative transfer models of the Jovian atmosphere using the modified Ben-Reuven lineshape for the absorption of gaseous ammonia (NH_3) appear to deviate from observations at millimeter-wavelengths. Laboratory measurements at both 32-40 GHz (7.5 - 9.3 mm) and 94 GHz (3.2 mm) have been completed and confirm that some modified form of the Ben-Reuven lineshape does accurately describe the observed opacity of gaseous ammonia under simulated Jovian conditions. Models of the absorption spectrum of ammonia are being derived from laboratory measurements at both microwave and millimeter-wavelengths. Radiative transfer models are being developed which utilize these laboratory results. The models can also be used to evaluate other potential sources of millimeter-wave opacity such as cloud condensates and gaseous hydrogen sulfide (H_2S).

*This work was supported by the Planetary Atmospheres Program of the National Aeronautics and Space Administration under Grant NAGW-533.

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DIVISION FOR PLANETARY SCIENCES ABSTRACT FORM

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Evidence for Temporal Variations in SO2 Abundance in the Sub-Cloud Region of the Venus Atmosphere

P.G. Steffes (Georgia Institute of Technology)

Analysis of 1987 measurements of the microwave emission of Venus from 1.3 to 3.6 cm (Steffes, et al., 1989, Icarus, in press) places limits on the abundance of SO_2 below the cloud layers (altitudes below 48 km). The SO_2 abundance inferred from these measurements is a factor of 3-4 below the abundances measured in 1978 by the Pioneer Venus Sounder Probe (Oyama et al., 1980, JGR 85, 7891) and by the Venera 12 lander (Gel'man et al., 1979, Cosmic Research 17, 585). However, our result is in agreement with results from the Vega 1 and 2 Probes obtained in 1985 (Bertaux et al., 1987, Cosmic Research 25, 691). This strongly suggests a decrease in the subcloud abundance of SO_2 in the period from 1978 to 1987, which parallels the observed decrease in SO_2 at the cloud tops by Esposito et al., (1988, JGR 93, 5267) and by Na et al., (1988, B.A.A.S. 20, 832).

*This work was supported by the Planetary Atmospheres Program of the National Aeronautics and Space Administration under Grant NAGW-533.

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BAAS VOL. ____ NO. ____

WYCHE FOWLER, JR.
GEORGIA

COMMITTEE ON APPROPRIATIONS

COMMITTEE ON AGRICULTURE, NUTRITION, AND FORESTRY

COMMITTEE ON THE BUDGET

United States Senate

WASHINGTON, D.C. 20510

July 20, 1989

Mr. Paul G. Steffes
Associate Professor
Georgia Institute of Technology
School of Electrical Engineering
Atlanta, Georgia 30332

Dear Mr. Steffes:

Thank you for letting me know of your support for a strong American space program and for the CRAF/Cassini missions.

I share your interest in this field and have been a strong supporter of maintaining a vigorous space policy throughout my service in Congress. As a world leader in this area, I strongly believe we should strive to expand our knowledge of the solar system and exploit the opportunities such knowledge provides. One of the primary national goals should be to preserve America's leadership in space sciences and technology and their applications for peaceful purposes.

In addition to expanding our role in space, the national space program continues to develop technologies and uncover information that serve our immediate needs on Earth. Our activities in space have produced and continue to yield significant information and advances in several diverse fields, including communications, meteorology, and the global environment. Ongoing and future space projects have provided or will provide important information about the atmosphere, ozone depletion, the destruction of our tropical forests, and a host of other vital issues.

I am happy to report the Bush Administration has requested a $13.3 billion dollar budget for NASA for fiscal year 1990. This is a 22% increase over the $10.9 billion NASA received this year and will allow NASA to pursue its several projects on schedule. As the Senate Appropriations Committee examines the Administration's budget proposal and makes a final decision on the 1990 budget, you can count on my support for a strong American space program.

I appreciate your interest in this important subject.

Sincerely,

WYCHE FOWLER, JR.
United States Senator

E-21-602

13

REPORT

TO THE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

<u>SEMIANNUAL STATUS REPORT #13</u>

for

GRANT NAGW-533

LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

Paul G. Steffes, Principal Investigator

November 1, 1989 through April 30, 1990

Submitted by

Professor Paul G. Steffes
School of Electrical Engineering
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I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing atmospheric constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. For example, laboratory measurements performed by Joiner et al. (1989), under Grant NAGW-533, have shown that the millimeter-wave opacity of ammonia between 7.5 mm and 9.3 mm and also at the 3.2 mm wavelength is best described by a different lineshape than was previously used in theoretical predictions. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements and to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

A key activity in the first half of this grant year has continued to be laboratory measurements of the microwave and millimeter-wave properties of the simulated atmospheres of the outer planets and their satellites. However, we have also focussed on development of a radiative transfer model of the Jovian atmosphere at wavelengths from 1 mm to 10 cm. This model utilizes our laboratory data and has also been used to evaluate the need for laboratory measurements of other possible absorbers. This modeling effort suggests that a laboratory measurement of the millimeter-wave opacity of hydrogen sulfide (H_2S) should be conducted. Similarly, it suggests that it may be possible to detect H_2S in the atmosphere of Jupiter using a medium resolution observation at 1.4 mm. Since no sulfur compounds have yet been detected in the Jovian atmosphere, this would be an important observation. A complete description of this modeling effort and the proposed observation are given in Section II and in Appendix A.

Recently, we completed measurement, calibration, and interpretive studies of the Venus microwave emission, and a paper entitled "Observations of the Microwave Emission of Venus from 1.3 to 3.6 cm," by P.G. Steffes, M.J. Klein, and J.M. Jenkins (Steffes _et al_., 1990) has been published in _Icarus_. (Reprints will be forwarded to NASA as soon as they are available.) One important issue which was discussed in this paper is the discovery that the microwave absorptivity for gaseous H_2SO_4 which was measured by Steffes (1985 and 1986) appears to differ from a theoretical spectrum newly computed by Janssen (personal communication) by a scale factor. That scale factor suggested that the theoretically-derived "dissociation factor" for gaseous H_2SO_4 (i.e., the percentage of H_2SO_4 which breaks down to form SO_3 and H_2O) may have been underestimated. This could result in an underestimation of the absorption from gaseous H_2SO_4. Therefore, an experiment has been conducted to correctly evaluate the "dissociation factor" and thus allow unambiguous calibration of laboratory data for H_2SO_4 opacity (see Section III). This is critical for the proper interpretation of a wide range of opacity data.

Another important tool for evaluating potential spatial and temporal variations in abundance and distribution of gaseous H_2SO_4 is the reduction and analysis of recently obtained Pioneer-Venus radio occultation measurements. The 13 cm microwave absorptivity profiles, which can be obtained from the radio occultation data, are closely related to the abundance profiles for gaseous H_2SO_4. Starting in 1988, we began the reduction of the 1986-87 Pioneer-Venus radio occultation measurements (working at JPL with support from the Pioneer-Venus Guest Investigator Program) in order to obtain the needed 13 cm microwave absorptivity profiles (Jenkins and Steffes, 1990). Yet another important source of information is the increasing number of high-resolution millimeter-wavelength Venus emission measurements which have been recently conducted. Correlative studies of these measurements with radio occultation measurements and our longer wavelength emission measurements (Steffes et al., 1990) should provide the necessary data for characterizing temporal and spatial variations in the abundance of gaseous H_2SO_4 and SO_2, and for modeling its role in the subcloud atmosphere. In fact, it appears from the results of Steffes et al., (1990) that long term temporal variations in subcloud SO_2 abundance are indeed occurring. (See Figure 1.1 and Appendix C) However, unambiguous results will require that we have dependable knowledge of the equilibrium between gaseous H_2SO_4, SO_3, and H_2O, both so as to properly interpret laboratory measurements of the microwave and millimeter-wave opacity of the gases which elute from liquid sulfuric acid, as well as to model their relation within the Venus atmosphere. Our results in

Section III provide this information.

In the second half of this grant year we intend to complete laboratory measurements of the 1.4 mm opacity of gaseous H_2S under simulated Jovian conditions and to use these results in refining our radiative transfer model. We will also begin measurements of the millimeter-wave properties of various gases and condensates (such as SO_2 and H_2SO_4) under simulated Venus conditions, with the goal of better characterizing any temporal or spatial variations in constituent abundances.

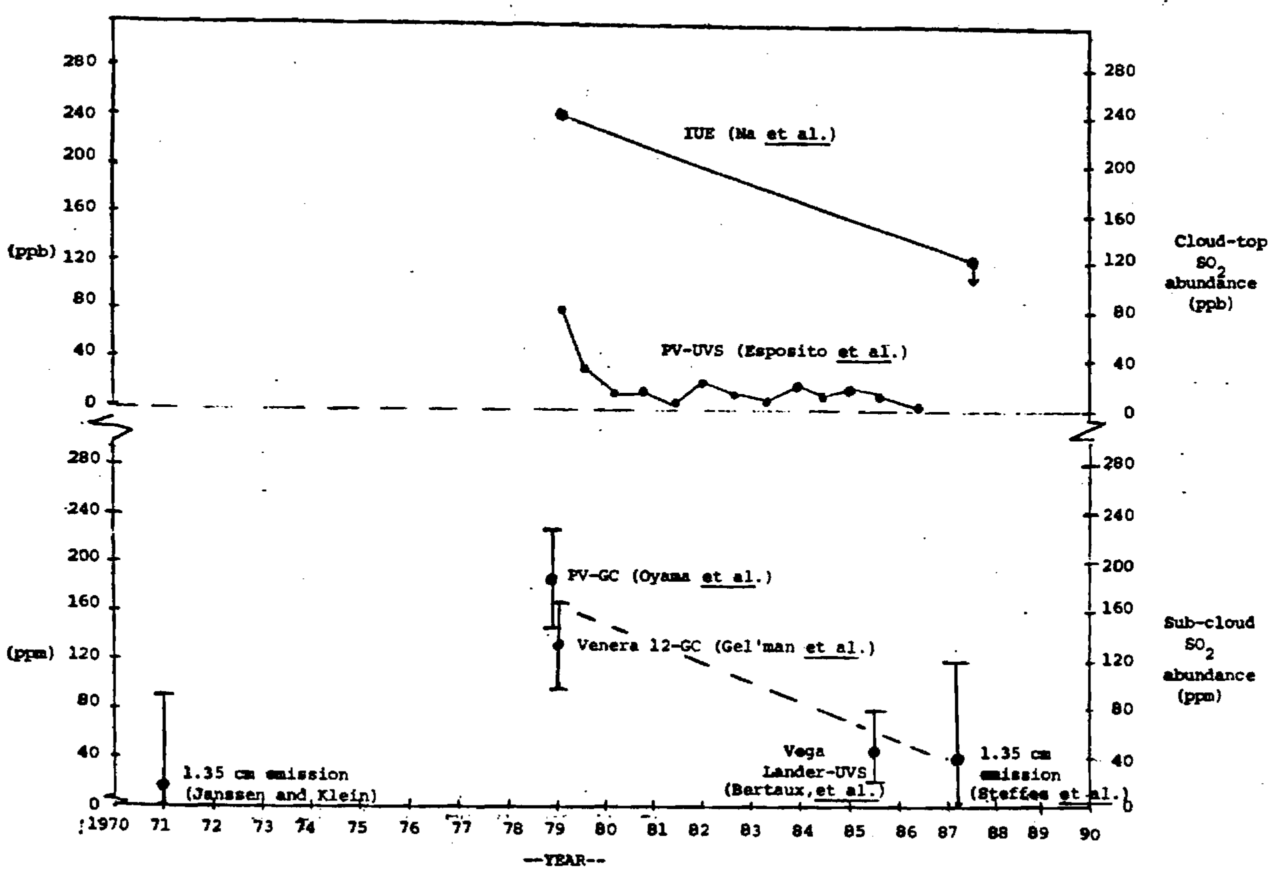


Figure 1.1: Comparison of measured variations of cloud-top SO_2 with those measured or inferred for sub-cloud SO_2.

II. OUTER PLANETS STUDIES

The basic configuration and technique for conducting the measurement of millimeter-wave absorptivity of gases under simulated conditions for planetary atmospheres is described at length in Semiannual Status Report #11 for Grant NAGW-533. Measurements of the absorptivity of gaseous ammonia under simulated Jovian conditions have been completed at both Ka-Band (32-40 GHz) and W-Band (94 GHz). A complete description of the theory for the ammonia absorption under Jovian conditions and the results of our laboratory measurements is given in the last Annual Status Report (includes Semiannual Status Report # 12) for Grant NAGW-533 (February 1,1989 - October 30, 1989).

During the first half of this grant year, we have continued development of a radiative transfer model of the Jovian atmosphere. This model utilizes our laboratory data and has also been used to evaluate the need for laboratory measurements of other possible absorbers. A general description of this program and its parameters is given in Semiannual Status Report # 12 for Grant NAGW-533.

We have studied the pressure-induced absorption from molecular hydrogen pairs (i.e., hydrogen-hydrogen, hydrogen-helium, and hydrogen-methane) and have derived new parameters for the expression given in Berge and Gulkis (1976) which was originally derived by Goodman (1969). This expression is given as

$$\alpha_{H_2} = 4e{-}11 P_{H_2} \cdot [P_{H_2} (\frac{273}{T})^{2.8} + 1.7 P_{He} (\frac{273}{T})^{2.61}] \cdot \lambda^{-2} \qquad (2.1)$$

A computer program was written to evluate the computationally intensive pressure-induced absorption from the six-parameter model in Borysow et al. (1985). New parameters for the temperature and pressure dependences in the Berge and Gulkis (1976) expression were fit to the Borysow et al. (1985) model. The new expression is

$$\alpha_{H_2} = 3.557e{-11}\, P_{H_2} \cdot [P_{H_2} (\frac{273}{T})^{3.12} + 1.3819 P_{He} (\frac{273}{T})^{2.24}] \cdot \lambda^{-2} \quad (2.2)$$

Graphs of the three formalisms are shown in Figures 2.1 and 2.2 for 30 and 300 GHz (1 cm and 1 mm) respectively. Our new expression deviates from the Borysow et al. calculation by less than 1% for pressure less than 10 bar. At pressures greater than 100 bar, our expression deviates from theirs by about 10%.

We have also completed a survey of the existing millimeter-wave observations of Jupiter. Figure 2.3 shows the radio observations from surveys in dePater and Massie (1985) and Berge and Gulkis (1976). In addition, the observations from Griffin et al. (1986) were added. A calculated emission spectrum from our model program which is similar to the models given in the dePater and Massie (1985) is also shown in this figure. We have reviewed all of these observations along with their calibrators and bandwidths. The sources and calibrators for the millimeter observations are labeled in Figure 2.4.

We note that there were several problems with some of the existing observations. For example, the measurement of Rather et al. (1974) used Jupiter as the calibrator. Since the temperature of Jupiter was assumed to be 150K, this observation is useful only for comparisons between Jupiter and the other planets and not as a basis of comparison between the observation and model spectra of

Jupiter. Likewise, the measurements of Low and Davison (1965) and Epstein (1970) which used the moon and sun respectively as calibrators are not reliable and should not be compared to measurements made with other calibrators such as Mars and DR21.

We have also updated our survey by including the corrections given by Klein and Gulkis (1978) who normalized all of the reliable observations between 0.8 and 2.1 cm to common flux scale based on Cassiopeia A (3C461). Figure 2.5 shows an updated graph of the observations after discarding the unreliable observations and including the updated calculations. The observations are classified according to calibration sources: Observations made with Mars as the primary calibrator are denoted by an 'o', absolutely calibrated measurements are denoted by 'x', and observations with various other calibrators such as DR21, Casseopia A, etc. are denoted by '*'. Note that the observations at the millimeter wavelengths are significantly lower than the calculated emission spectrum. We have examined the effects of using different abundance and absorption profiles for various molecules in our model program in an attempt to explain the discrepancy between the models and the observations.

We have evaluated several different ammonia abundance profiles using our radiative transfer model. Three of these profiles are shown in Figure 2.6 where dPM 1985 refers to dePater and Massie (1985). The dePater (1986) profile is a more realistic profile where the abundance decreases more gradually. The enhanced profile adds slightly more ammonia. Three model calculations for these profiles which use the Berge and Gulkis (1976) formalism of the

Ben-Reuven lineshape for ammonia absorption are shown in Figure 2.5. We have also studied the effect of changing the lineshape used to calculate the absorption from ammonia on the calculated emission spectra. Figure 2.7 shows model spectra for the 'enhanced' ammonia abundance profiles using two different formalisms of the Ben-Reuven lineshape for computing the absorption due to ammonia. Spilker and Eshleman (1988) have developed a formalism using the Ben-Reuven lineshape based on high accuracy measurements of ammonia at microwave frequencies. The model calculations using the enhanced profile with the Spilker and Eshleman (1988) formalism for ammonia abundance (labeled BR-SE) are consistent with radio astronomical observations in the microwave region. However, the Spilker and Eshleman formalism in its present form is not accurate at millimeter wavelengths. As reported in Annual Status Report #12 for Grant NAGW-533, the Berge and Gulkis formalism for the Ben-Reuven lineshape (BR-BG) should be used at millimeter wavelengths. Note that the effect of adding H_2S to the model with ten times the solar amount at pressures greater than 1.8 bar is also shown in this figure. Absorption from H_2S will be discussed in detail later in this report. In order for the model to account for the large bandwidths of many of the observations (on the order of 75 GHz), the contributions from the H_2S lines were averaged over 75 GHz (equivalent to convolving the spectrum with a 75 GHz flat filter). It is seen that the averaged contribution from H_2S is small when compared to the contribution from ammonia. Therefore, information regarding H_2S in the lower atmosphere cannot be inferred from the existing large bandwidth observations.

Figure 2.8 shows a single calculated spectrum where we have used the Spilker and Eshleman formalism at centimeter wavelengths, the Berge and Gulkis formalism at the shorter millimeter wavelenghts, and a smooth transition between the two from about 5 to 7 mm. We have also included the averaged contribution from H_2S. This model calculation is much more consistent with the observations than previous models (those similar to dePater and Massie, 1985). However, the observations using Mars as the calibrator are still consistently lower than the model. Griffin et al. (1986) note that uncertainty in the models for Mars are as great as 10%. Orton (private communication) put the uncertainty closer to 20%.

In Figure 2.9, we examine the effect of raising all of the Mars calibrated observations by 5% as was previously done in Griffin et al. (1986). It should be noted that the 'absolutely' calibrated observation by Ulich et al. at 1.4mm may contain an additional offset. This observation did not use a true absolute calibration, but used models of the emission at both higher and lower frequencies in order to derive the calibration. Therefore, as dePater and Massie (1985) noted, it could contain an additional offset of at least 5%. Raising this observation by 5% is shown with a dotted line. If we also raise the Courtin et al. (1977) observation by an additional 5% (this was an isolated measurement as opposed to the measurements of Griffin et al. (1986) at several wavelengths), we see a very good agreement between the observations and model calculations. The discrepancy between the models and the observations may therefore be due entirely to uncertainty in the calibration and not to some other absorber. However, until more reliable observations with absolute calibration are made, it cannot be determined as to how much uncertainty in the calibration, absorption from sources such as H_2S or cloud condensates, or a combination of these factors is affecting the observed spectra at millimeter wavelengths.

One potential absorber at millimeter wavelengths which we have examined closely is gaseous hydrogen sulfide (H_2S). Three strong lines of H_2S appear in the millimeter spectrum at 168, 216 and 300 GHz. We have developed a model of hydrogen sulfide absorption based on line strengths given by Helminger et al. (1972). The line widths and broadening parameters for this gas have never been measured and can only be estimated. The Van Vleck-Weisskopf lineshape was used in our calculation with the linewidths estimated from those of water vapor (H_2O) in an H_2/He atmosphere. The calculated absorption from H_2S under Jovian conditions for approximately ten times solar abundance (4×10^{-4} by volume) is shown in Figure 2.10.

Several different calculated emission spectra for Jupiter using various H_2S distributions for two different ammonia distributions are shown Figure 1 of Appendix A. An expanded view of the line at 216 GHz is shown in Figure 2 of Appendix A. The spectra show that detection of H_2S at this frequency is possible using a small bandwidth (on the order of 1 GHz or less) receiver. At least three radio telescopes with such receivers exist. We have written proposals to the Caltech Submillimeter Observatory (CSO) at Mauna Kea and the University of Massachusetts Millimeter

Observatory (Appendix A). We are also investigating the use of the NRAO Observatory at Kitt Peak. Thus far, we have been granted observing time in November 1990 at the CSO (see Appendix B).

In order to interpret the results of this observation, the behavior of H_2S under Jovian conditions must be examined in a laboratory environment. Analysis of Figure 2.10 shows that by using higher concentrations of H_2S in an H_2/He atmosphere, absorption should be detectable in the laboratory. However, the lines of H_2S occur at much higher frequencies (168, 216, and 300 GHz) than previous laboratory experiments (NH_3 was measured at 40 and 94 GHz). The signal source used to measure absorption at these frequencies would have to be harmonically generated. The use of a frequency doubler in order to achieve harmonic generation would decrease the signal strength and thus the signal to noise level would be lower than that of previous experiments. We are currently investigating the feasibility of making a laboratory measurement of H_2S at 216 GHz. Some of the equipment, such as a resonator (if needed), source, mixers, and waveguide could be supplied by the Georgia Tech Research Institute (GTRI). This experiment would probably be conducted at room temperature since the equipment would be too big to fit in our ultra low temperature freezer. Since H_2S is extremely opaque near the line centers, it may be possible to measure its absorptivity using a long glass cell with a source and precision attenuator at one end and a detector at the other. This would greatly simplify the measurement since a resonator would not be necessary. We hope to have a laboratory measurement of H_2S completed in the last half of the current grant year.

Another potential absorber at millimeter wavelengths is cloud condensates. We have developed a model for the absorption due to cloud condensates based on Rayleigh scattering. In the Rayleigh regime, the absorption in optical depths per meter is expressed by

$$\alpha = \frac{18\pi M}{\rho\lambda} \cdot \left[\frac{\epsilon''}{(\epsilon'+2)^2+\epsilon''^2}\right] \tag{2.3}$$

(Battan, 1973) where ρ is the density of the condensation particle given in g/cm^3, M is the bulk density of the cloud in the same units, λ is the wavelength in m, ϵ' and ϵ'' are the real and imaginary parts of the complex dielectric constant of the cloud material. The quantities can be related to the real and imaginary parts of the index of refraction through the following relationships:

$$\hat{\epsilon} = \epsilon' - j\epsilon' \tag{2.4}$$

$$\hat{n} = n - jk \tag{2.5}$$

$$\hat{\epsilon} = \hat{n}^2 \tag{2.6}$$

$$\epsilon' = n^2 - k^2 \tag{2.7}$$

$$\epsilon'' = 2nk \tag{2.8}$$

Using Eq. 2.3 along with a model for the cloud bulk desity from Romani (personal communication), we have added cloud opacity to our Jovian model. The cloud bulk densities are shown in Figure 2.11. Since the complex index of refraction of ammonia at these wavelengths is not known, we extrapolated values from measurements in the infrared from Sill et al. (1980). We use a value of 1.3 for n, the real part, and 0.05 for k, the imaginary part of the index of refraction. These values are the same as used by dePater and Massie (1985) and represent the maximum possible contribution from cloud opacity. Contrary to the findings of dePater and Massie (1985), our calculations show that given these assumptions for the index of refraction of solid ammonia, clouds may indeed contribute to the opacity of Jupiter's atmsphere.

Figure 2.12 shows a model in which the cloud opacity is included. Note that the model spectra in which cloud opacity is included provide a much better fit than those without cloud opacity. The dip in emission at 216 GHz from H_2S is still visible and thus should still be observable given the conditions for maximal cloud absorption.

During the next six months we will continue to improve our atmospheric model. The model will be modified in order to take into account the oblateness of the planet. It will also be enhanced by adding a spatial resolution capability. We will also begin to develop and incorporate our own cloud models into the radiative transfer program. In the laboratory, we will aquire all the necessary equipment and complete a measurement of the H_2S pressure broadened line at 216 GHz. This laboratory data will be very important in analyzing the planned November 1990 observation of Jupiter in which we will be looking specifically at the 216 GHz line of H_2S.

Figure 2.1:

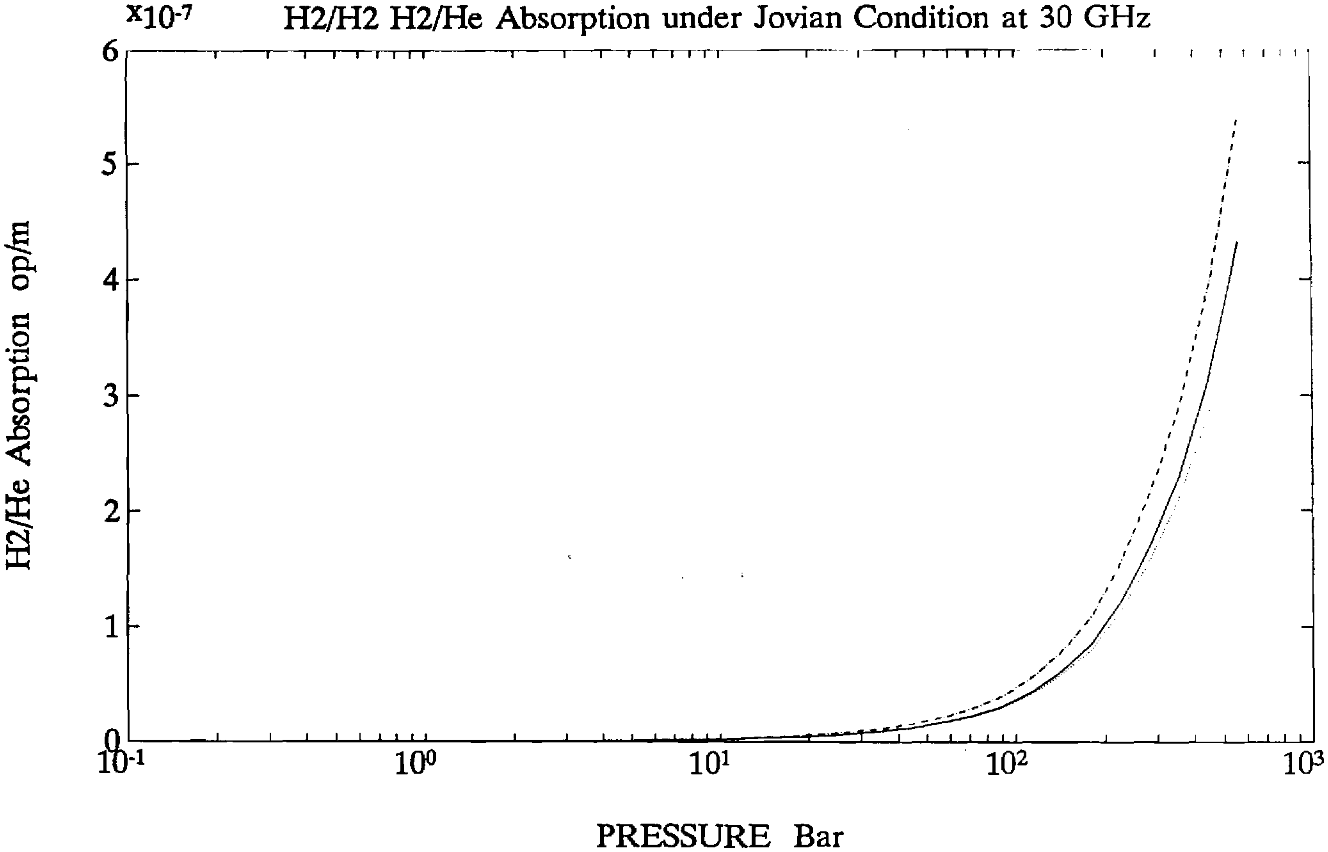


Figure 2.2:

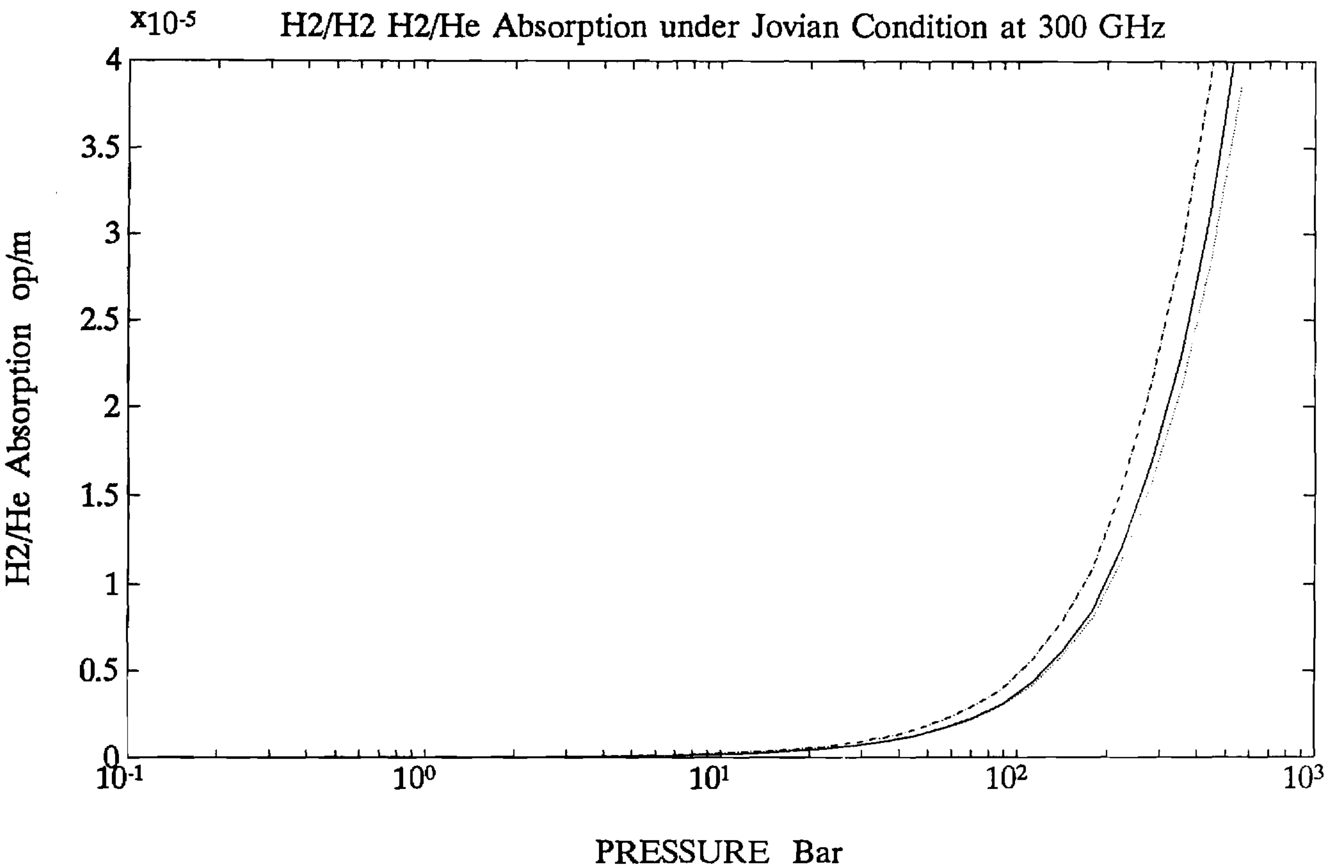


Figure 2.3: Jovian model B&G NH3 DPM

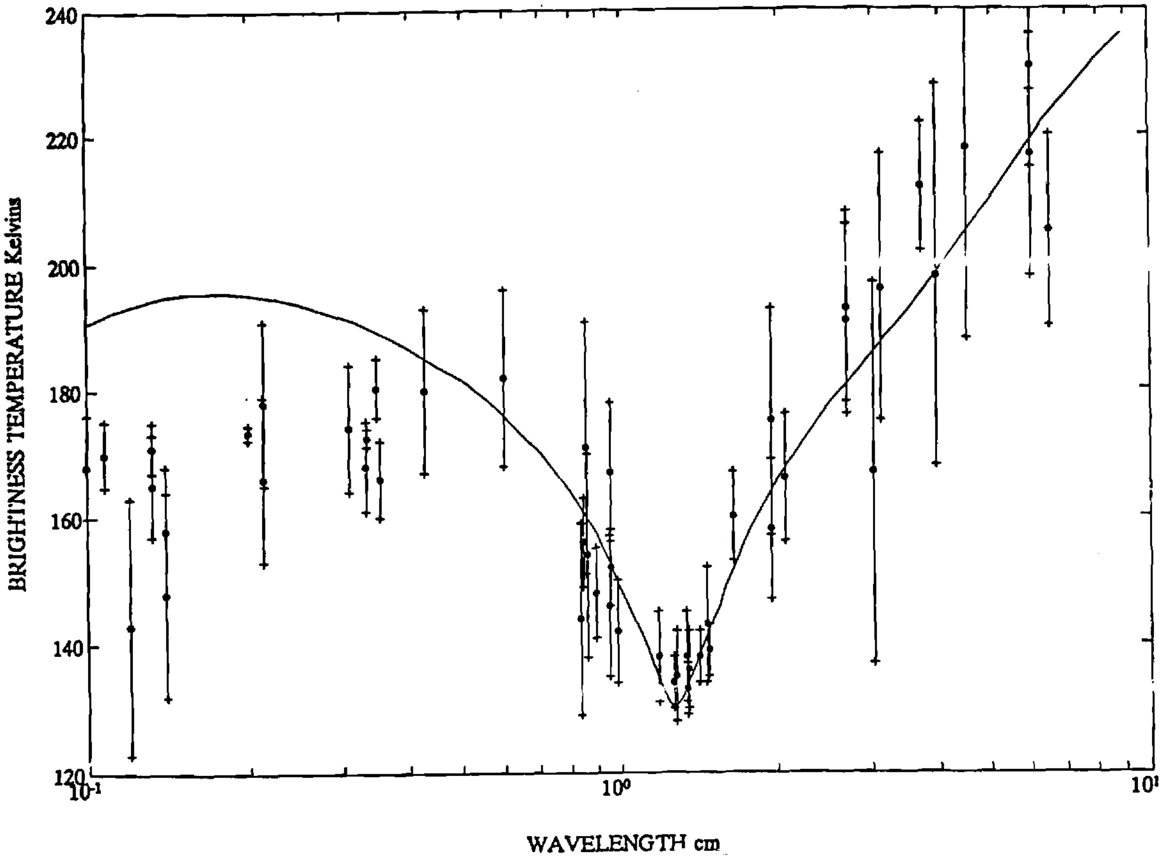


Figure 2.4: Jovian model B&G NH3 DPM

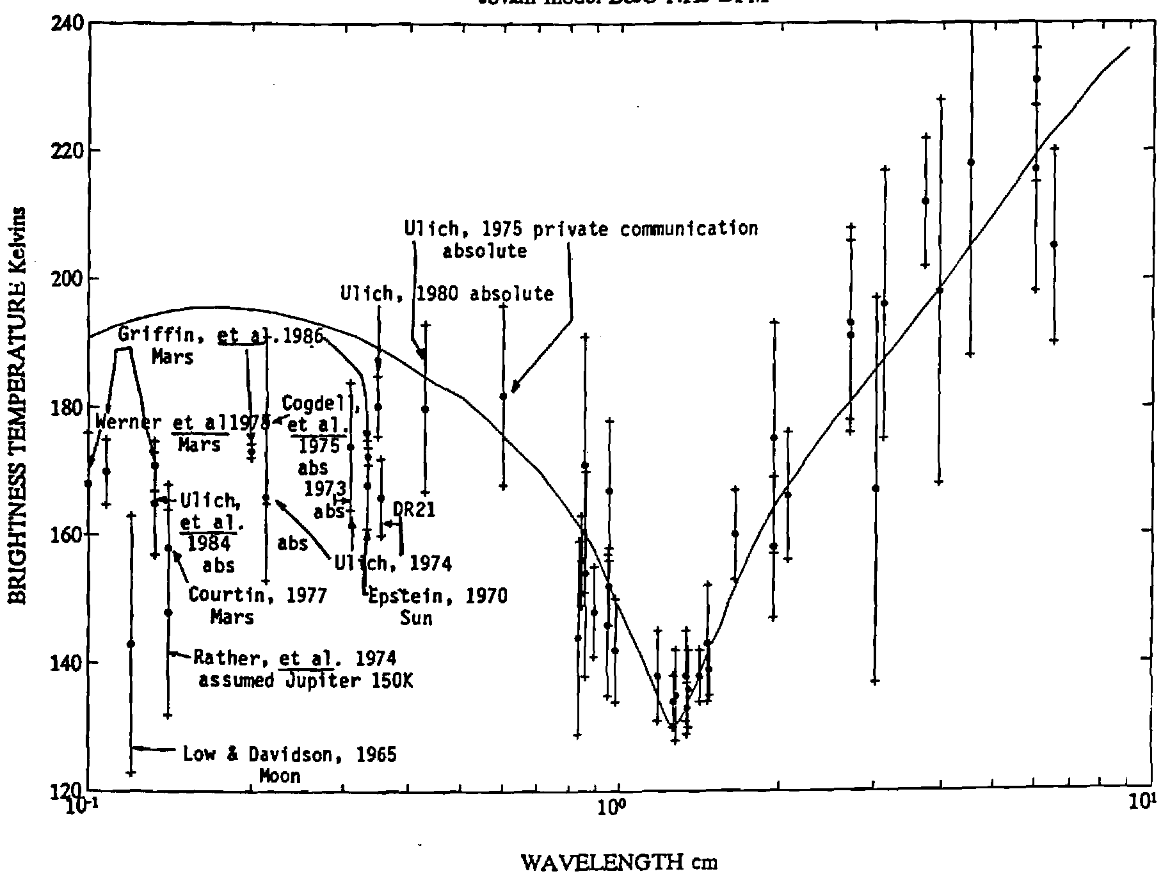


Figure 2.5: Various models of Jovian emission for B&G Ben Reuven

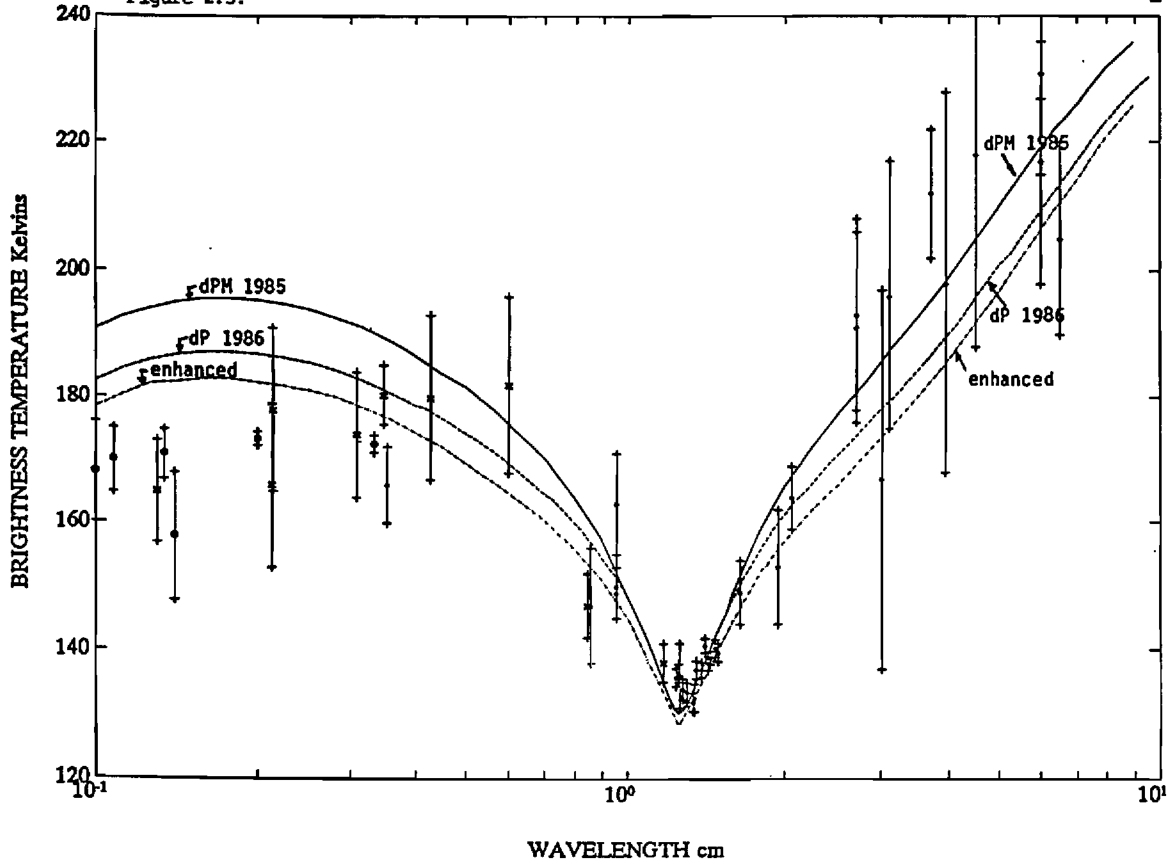


Figure 2.6: Various Ammonia Abundance Profiles from dePater 1986

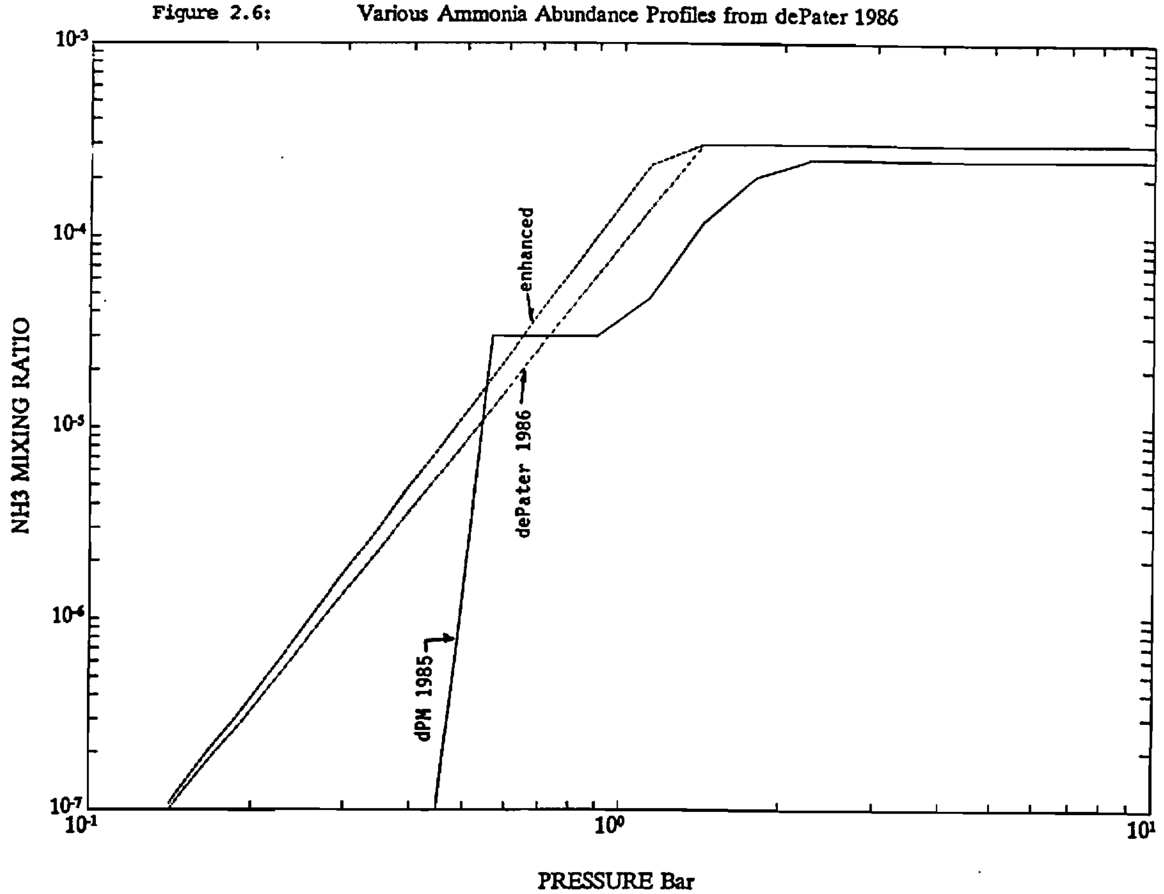


Figure 2.7: Jovian emission with enhanced NH3, B&G S&E NH3 absorption

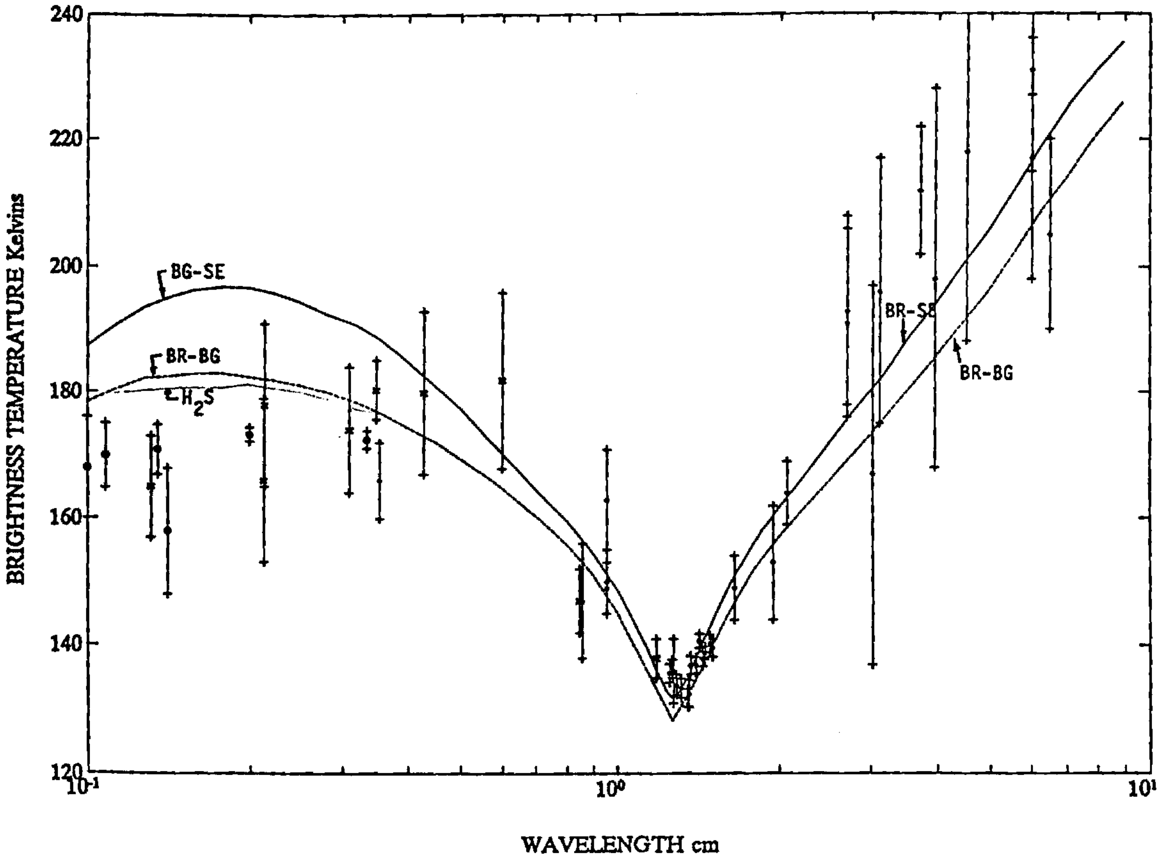


Figure 2.8: Jovian emission utilizing lab measurements

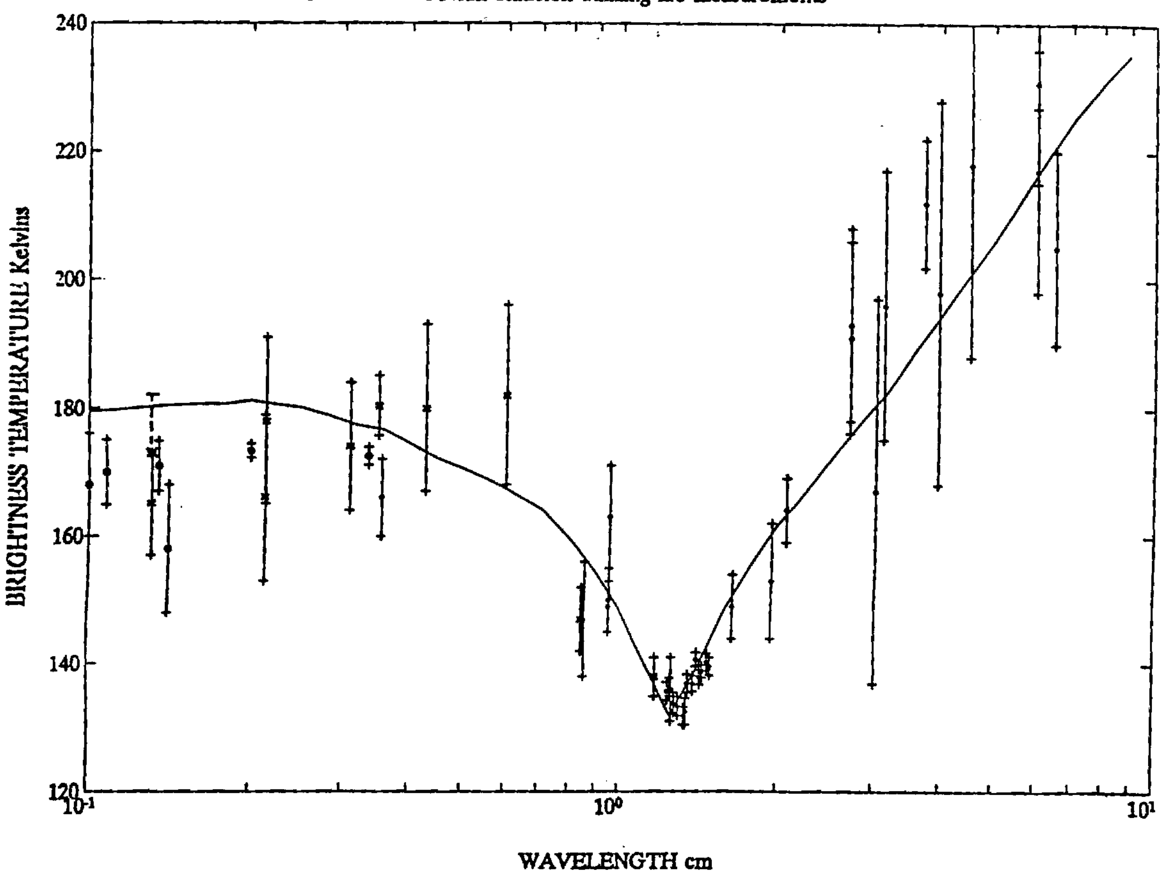


Figure 2.9: Jovian emission with Mars cal. observations raised 5%

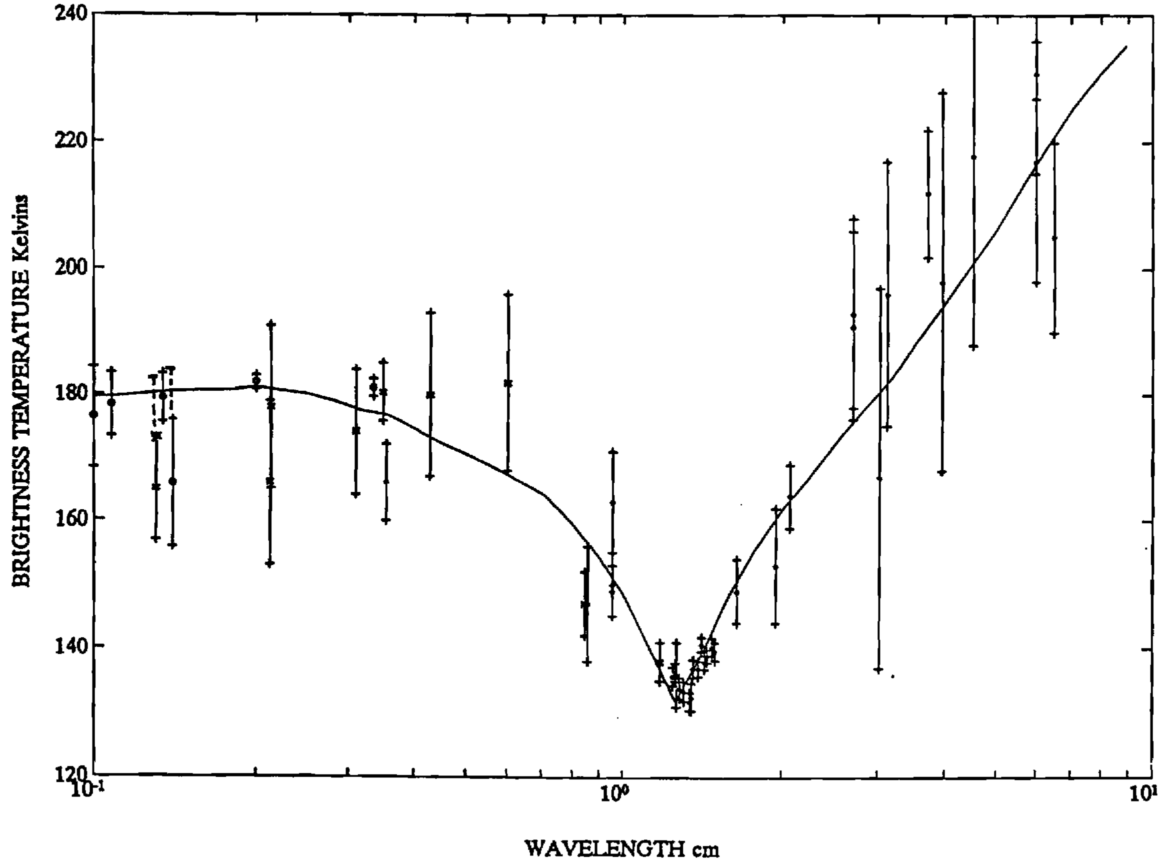


Figure 2.10: H2S Absorption XH2S=4e-4 XH2=.9 XHe=.1 T=200K P=2 atm (10X Solar H_2S)

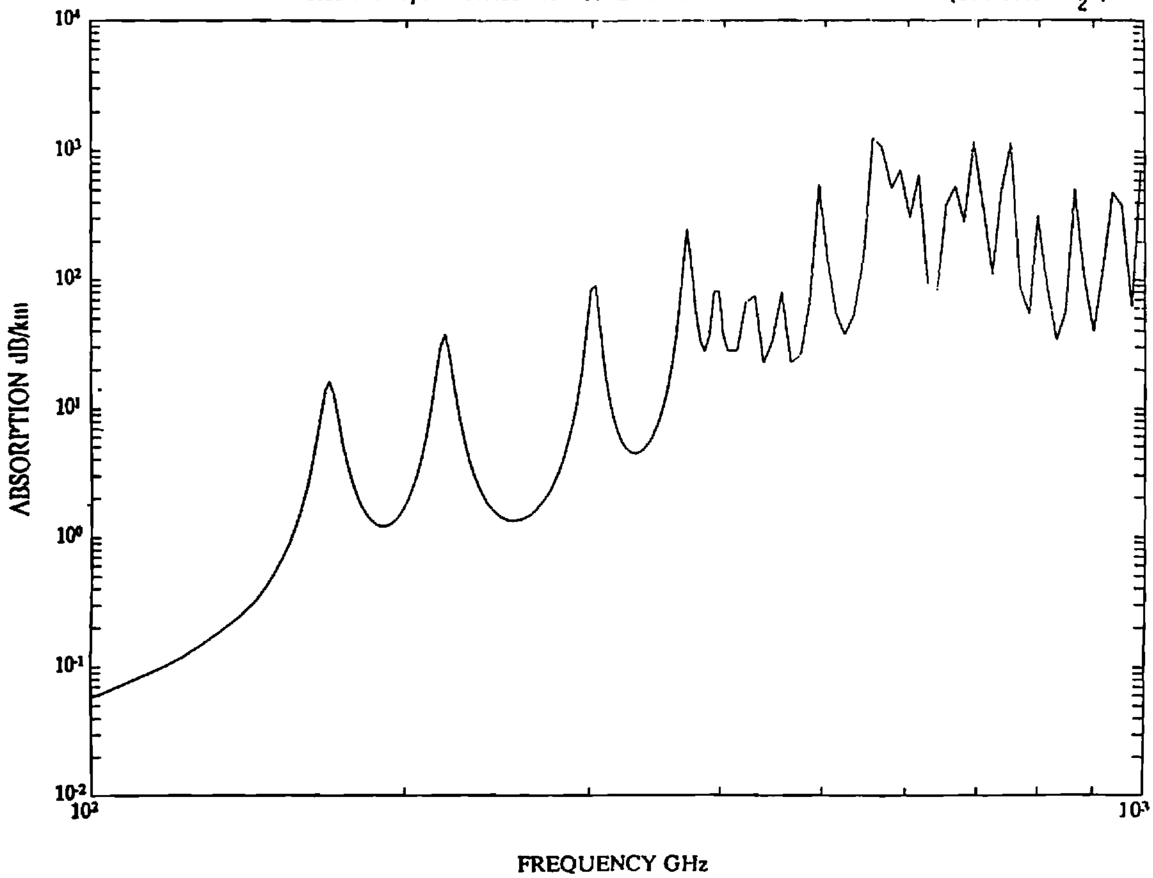


Figure 2.11: Cloud Model for Jupiter

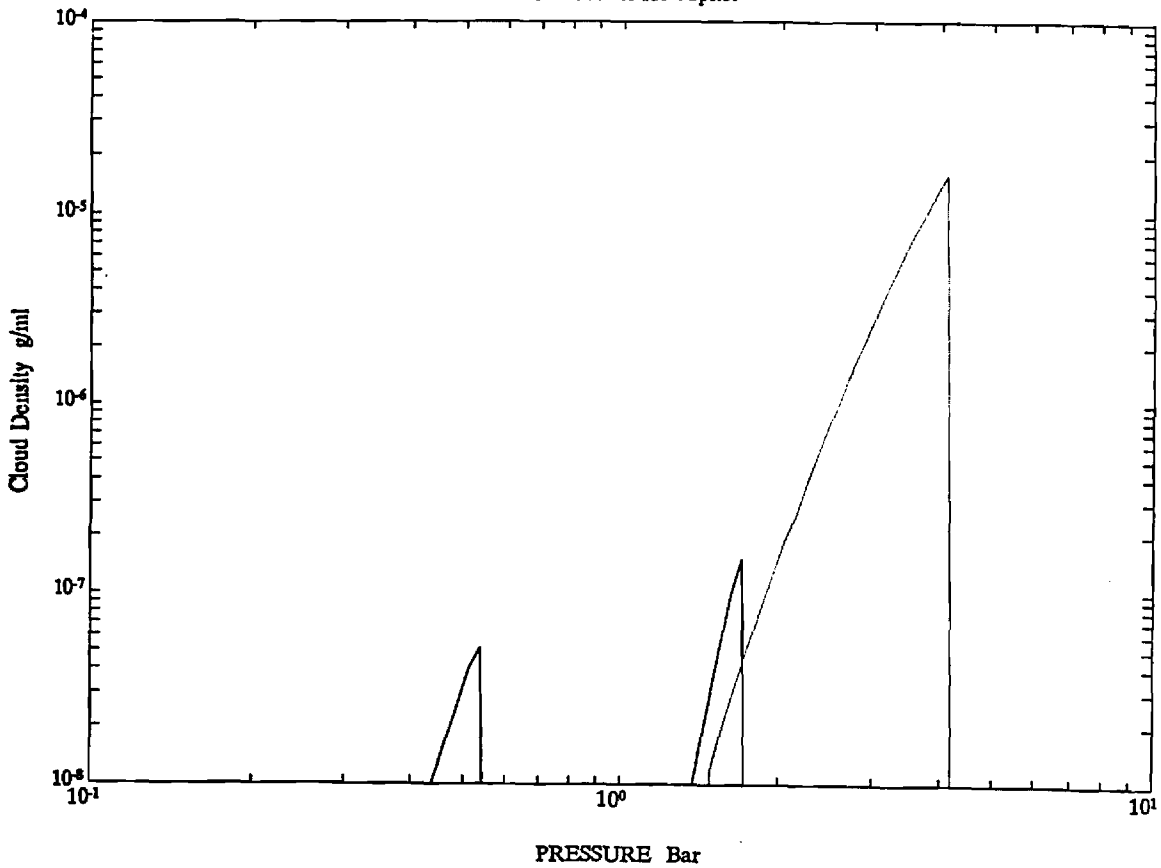
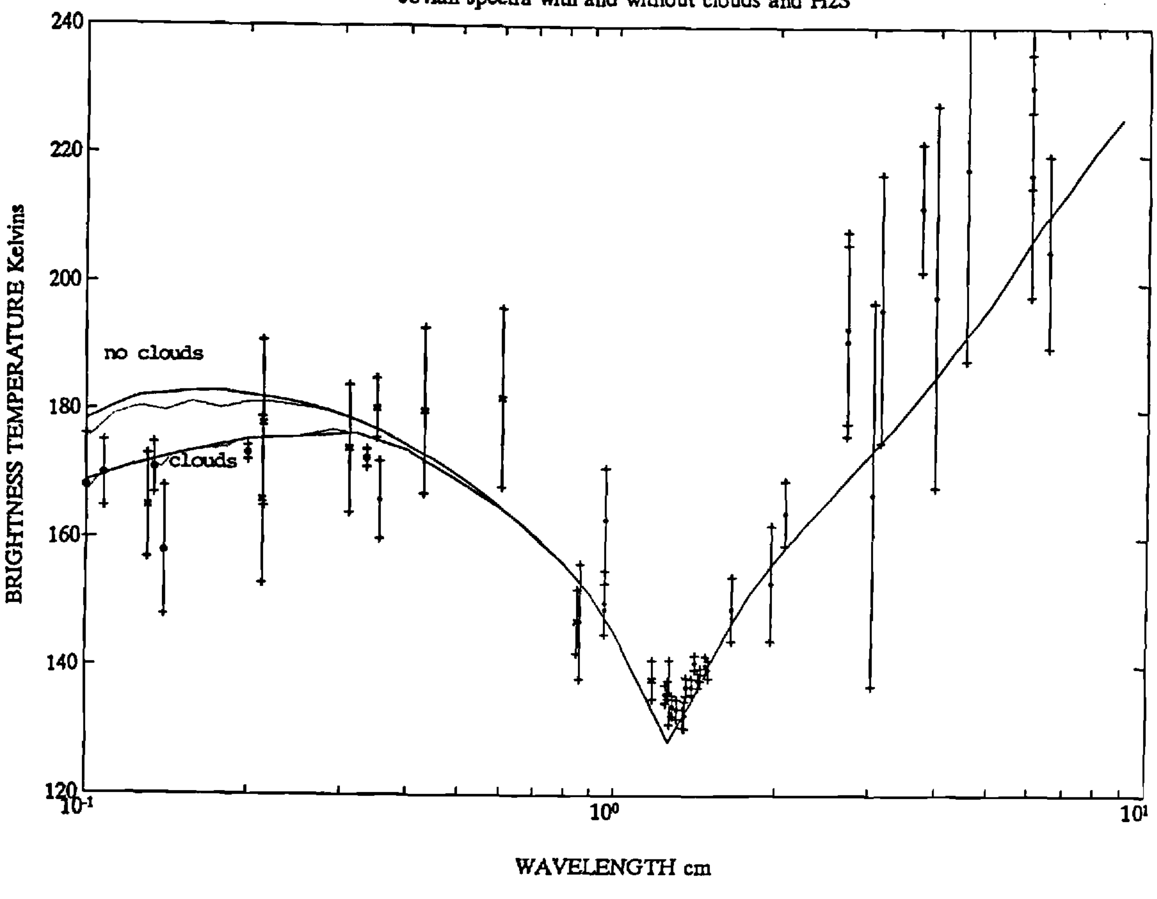


Figure 2.12 Jovian spectra with and without clouds and H2S



III. VENUS STUDIES

As discussed in the last Annual Status Report (February 1, 1989 through october 31, 1990) for Grant NAGW-533, the laboratory measurement of the dissociation factor of gaseous H_2SO_4 in equilibrium with liquid sulfuric acid is of great importance. In the past, Steffes (1985,1986) estimated that about 47% of gaseous H_2SO_4 that vaporized from a liquid sulfuric acid reservoir at 575 K dissociated to form gaseous SO_3 and H_2O. Although this estimation resulted in adequate results for an upper limit of gaseous H_2SO_4 vapor pressure, a direct measurement of the dissociation factor is necessary.

In the first half of this grant year, a complete development of a system capable of such measurements has been achieved. The apparatus can be used to measure the dissociation factor of gaseous sulfuric acid over a wide range of temperatures. As a result, a corrected expression for the measured pressure dependence of the microwave absorptivity (normalized by the number of mixing ratio) for gaseous H_2SO_4 in a CO_2 atmosphere at 2.2 GHz has been developed. In addition, a new expression for the saturation abundance of gaseous H_2SO_4 in the middle atmosphere of Venus has been developed. These resulting expressions can be used to infer the mixing ratio of gaseous sulfuric acid in the atmosphere of Venus provided that the absorption from the atmosphere of Venus is known. The determination of the mixing ratio of gaseous H_2SO_4 using the above expressions is currently being performed by Jenkins and Steffes (1990).

A. MEASUREMENT TECHNIQUE

The apparatus developed for the measurement of the dissociation factor of gaseous sulfuric acid is shown in Figure 3.1. In this setup, a large chamber (of known volume) is constructed using Pyrex glass as shown in Figure 3.2. The whole system is contained inside a temperature controlled oven. A special temperature controller was designed to precisely control the oven temperature which is measured using a pre-calibrated thermocouple.

The measurement procedure can be summarized as follows: The oven is first heated to the desired temperature. Once this temperature is achieved, a vacuum is drawn. By using gauge P1 as a vacuum monitor, we are able to monitor the status of the vacuum chamber. Although no leak-proof vacuum was obtained, we were able to keep the leaks within the system to approximately 1 Torr/hour. The minimization of these leaks have a major effect on the calculation of the dissociation factor since any substantial leaks in the system can alter the measured pressure from gauge P2. At the desired temperature, the flask valve is opened allowing the sulfuric acid liquid to reach vapor pressure equilibrium with the evacuated chamber. Once equilibrium is reached, the flask valve is closed and a visual check is made to verify that the remaining liquid acid is clear. After the flask's valve is closed, the valve connecting the nitrogen buffer and gauge P2 is opened and the resulting chamber pressure is recorded. It is important to emphasize that throughout this process, the system temperature had to be within certain limits of the desired value thus allowing the temperature variation factor to be minimal. In this case we were able to maintain the oven temperature to within ± 5 Kelvins. Once the pressure is recorded, the oven is shut off and the gaseous sulfuric acid is carefully evacuated from the chamber. The system is then allowed to cool overnight to its original room temperature. At that point, the remaining volume of liquid sulfuric acid is measured and the evaporated volume is inferred.

The determination of the dissociation factor can then calculated using,

$$D = \frac{98\, P_{NeT}\, V_{Chamber}\, (PCM + \rho_{H_2SO_4}\, (1 - PCM\,))\, -\, (V_{Liquid}\, PCM\, \rho_{H_2SO_4}\, R\, T)}{V_{Liquid}\, PCM\, \rho_{H_2SO_4}\, R\, T} \tag{3.1}$$

where PCM is the percent concentration of the liquid, $V_{Chamber}$ is the chamber volume, V_{Liquid} is the volume of the evaporated liquid, P_{Net} is the net measured pressure, R is the ideal gas constant and T is the temperature in K.

Thus if the chamber volume, the system temperature, the density of liquid sulfuric acid, the pressure resulting from the evaporated liquid acid, and the amount of the evaporated liquid are known, then a direct application of equation (3.1) will give the dissociation factor of the gaseous sulfuric acid. As a result of the calculated dissociation factor D, the partial pressure of gaseous H_2SO_4 can then be calculated. The partial pressure of gaseous H_2SO_4 ($P_{H_2SO_4}$) can be written as,

$$P_{H_2SO_4} = \frac{P_{Net}\ (\,1\, -\, D\,)}{(\,1\, +\, D\,)} \tag{3.2}$$

Thus the partial pressure of gaseous sulfuric acid can be computed from equation (3.2) provided that the net pressure measured and the resulting dissociation factor are known. One can also calculate the equilibrium constant, K_p, from the dissociation factor and the partial pressure of gaseous H_2SO_4. This calculation serves as a comparison between our results and the ones reported by Gmitro and Vermeulen (1964) and it will aid in correcting the partial pressure of H_2SO_4 at temperatures below 460 K. which were reported by Ayers et al.(1980).

B. MEASUREMENT RESULTS

The measurements were carried out on two liquid H_2SO_4 samples, each having a different concentration. The measurements reported in this report were made at six distinct temperatures ranging from 460 to 610 K. The lower temperature point is dictated by the sensitivity of the gauge P2 and its ability to accurately measure pressures below 1 atm while the upper bound on the temperature range is dictated by the maximum allowable temperature of the oven and the ability of some parts in the system to withstand these high temperatures.

The partial pressure of gaseous H_2SO_4 for 99% (by weight) is shown in Figure 3.3. In this figure, the illustrated points are from the laboratory measurements where the error bars indicate a worst case calculation of the partial pressure while the solid line is a best fit model of the data according to the Clausius-Clapeyron model. From the best-fit model, a temperature dependence of the vapor pressure of gaseous sulfuric acid for temperatures between

460 and 610 K can be written as,

$$\ln p = 6.36 - \frac{5952}{T} \qquad (3.3)$$

where p is the sulfuric acid vapor pressure (atm) and T is the temperature in Kelvins. A similar result is obtained for 95.9% and is shown in Figure 3.4. The best fit expression for the latter concentration is given by,

$$\ln p = 5.74 - \frac{5747}{T} \qquad (3.4)$$

A careful examination of the two figures reveals that the best-fit expression agrees with the measured data except for temperatures above 600 Kelvins where a deviation from the best fit model is observed. The laboratory measurements seem to indicate that a saturation pressure is occurring at these high temperatures while the best fit model indicates a further increase in the partial pressure of gaseous sulfuric acid. This observed phenomena is not yet fully understood but one can speculate that the Clausius-Clapeyron model may not be valid candidate for these high temperatures and an alternate model may be required.

A comparison between our results and the ones reported by Steffes(1985) Ayers et al. (1980) and Gmitro and Vermeulen(1964) is shown in Figure 3.5. An examination of this figure reveals that Steffes overestimated the partial pressure for high temperatures while he underestimated the partial pressure for temperatures below 510 K. This deviation may be attributed to the fact that Steffes did not measure the dissociation factor but he assumed a 47% dissociation factor over the measured temperature range. The comparison between our results and the extrapolation of the results reported by Ayers et al. shows that Ayers et al. overestimated the partial pressure of gaseous sulfuric acid. This discrepancy may be due to the fact that Ayers et al. did not determine the partial pressure of H_2SO_4 at these high temperatures (Ayers et al. results were reported for temperatures ranging between 338 to 445 K).

A further examination of the results reported in Figure 3.5 indicates that the dissociation factor increases as the concentration of liquid acid is decreased. This is to be expected since a lower acid concentration yields a decrease in sulfuric acid vapor pressure. In addition, an examination of the best fit models for the two concentrations indicates that their slope did not change with acid concentration which suggest that the partial pressure is proportional to the concentration of liquid sulfuric acid. Thus as the concentration of the acid decreases so does its vapor pressure.

A direct application of the above results can be clearly seen in Figure 3.6 which represents the corrected pressure dependence of the microwave absorptivity (normalized by the mixing ratio) for gaseous sulfuric acid in a CO_2 atmosphere at 2.2 GHz. The uncorrected data were reported by Steffes (1985) in which he used the partial pressure resulting from an assumed 47% dissociation factor. As a consequence of our measurements, the measured absorptivity was readjusted to account for the variation of the dissociation factor with temperature. In Figure 3.6, the dashed line represents a best-fit multiplicative expression for the absorptivity given as,

$$\alpha_{13}\ (dB\ km^{-1}) = 9.57\times10^{9}\ q\ (\ P\ )^{.54}\ (\ T\ )^{-3} \qquad (3.5)$$

where q is the sulfuric acid mixing ratio, P is the pressure in atm and T is the temperature in Kelvins. The error bars shown in figure (6) represent $\pm$ 1σ errors in the absorptivity measurements but do not include uncertainties in the mixing ratio.

In order to use the above results toward the determination of the saturation abundance and the mixing ratio of the gaseous sulfuric acid in the atmosphere of Venus, one needs to evaluate the partial pressure of H_2SO_4 at lower temperatures (330 to 460 K). A direct extrapolation of our results to lower temperatures may not be a valid calculation since the Clausius-Clapeyron model can greatly diverge from the expected partial pressure (a similar deviation was reported for the high temperature case). To accurately determine the partial pressure of H_2SO_4 at lower temperatures, it is necessary to compute a new equilibrium constant, K_p, for that temperature range and use the results reported by Ayers et al. to recalculate the new partial pressure. Thus by simply knowing the total pressure measured by Ayers et al., the corresponding partial pressure of H_2O and the respective K_p, one can easily calculate the resulting partial pressure of gaseous H_2SO_4. As a result, a best fit expression for the partial pressure of gaseous H_2SO_4 according to our K_p can be expressed as (330 to 460 K),

$$\ln p = -\frac{10210}{T} + 16.4 \qquad (3.6)$$

where p is the pressure in atmosphere and T is the temperature in Kelvins. The complete plot of the partial pressure of gaseous sulfuric acid as a function of the temperature is shown in Figure 3.9.

The above results are valuable in understanding the formation of the clouds in the middle atmosphere of Venus. Our results used in conjunction with other published data (Seiff, et al. 1980) will aid in the determination of the saturation abundance of gaseous sulfuric acid and will help in the determination of the mixing ratio of H_2SO_4 in the atmosphere of Venus.

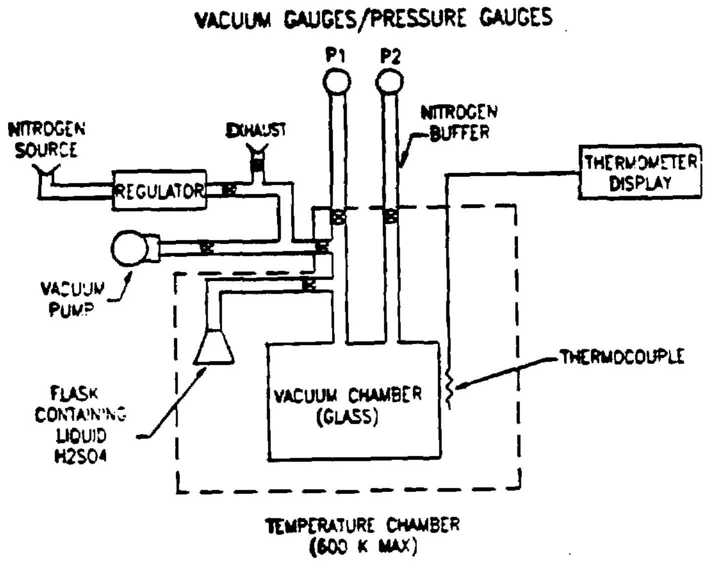


Figure # 3.1 Laboratory apparatus used to measure the dissociation factor D, for gaseous sulfuric acid above liquid phase.

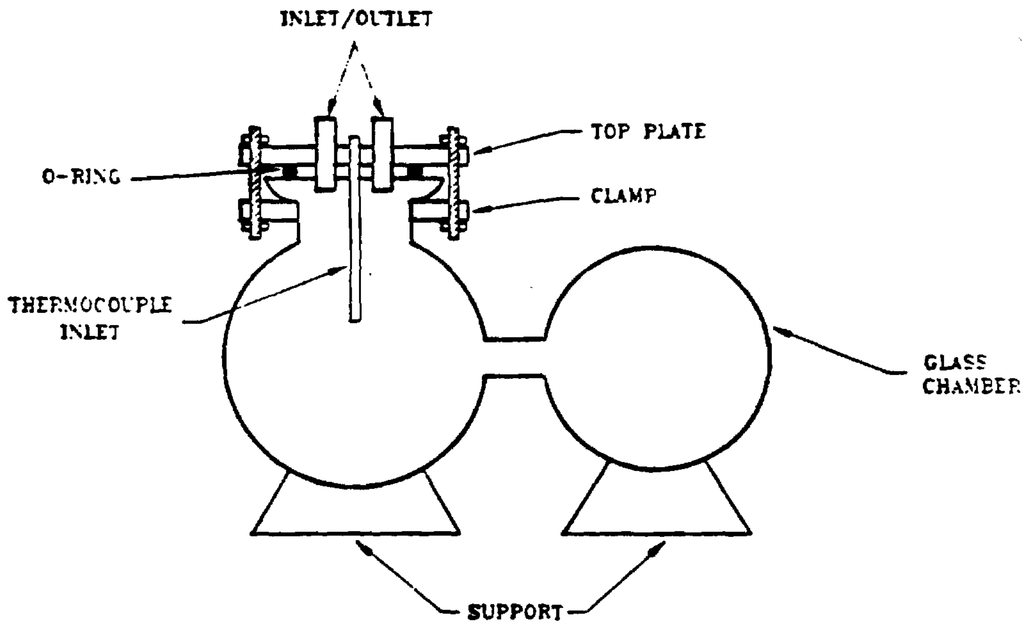


Figure 3.2 : Cross section view of the vacuum chamber used in our apparatus.

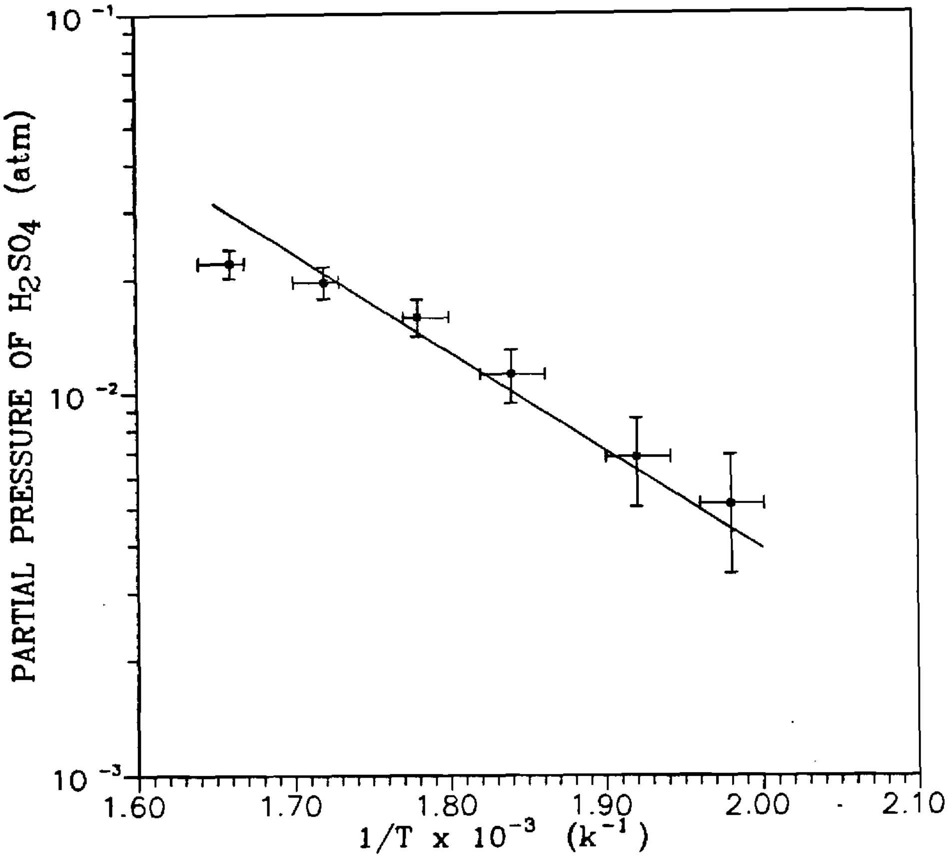


Figure 3.3 : Vapor pressure of gaseous sulfuric acid (99 %) as a function of temperature. the illustrated points are from laboratory measurements while the solid line represents a best-fit model. Error bars for pressure and temperature are shown.

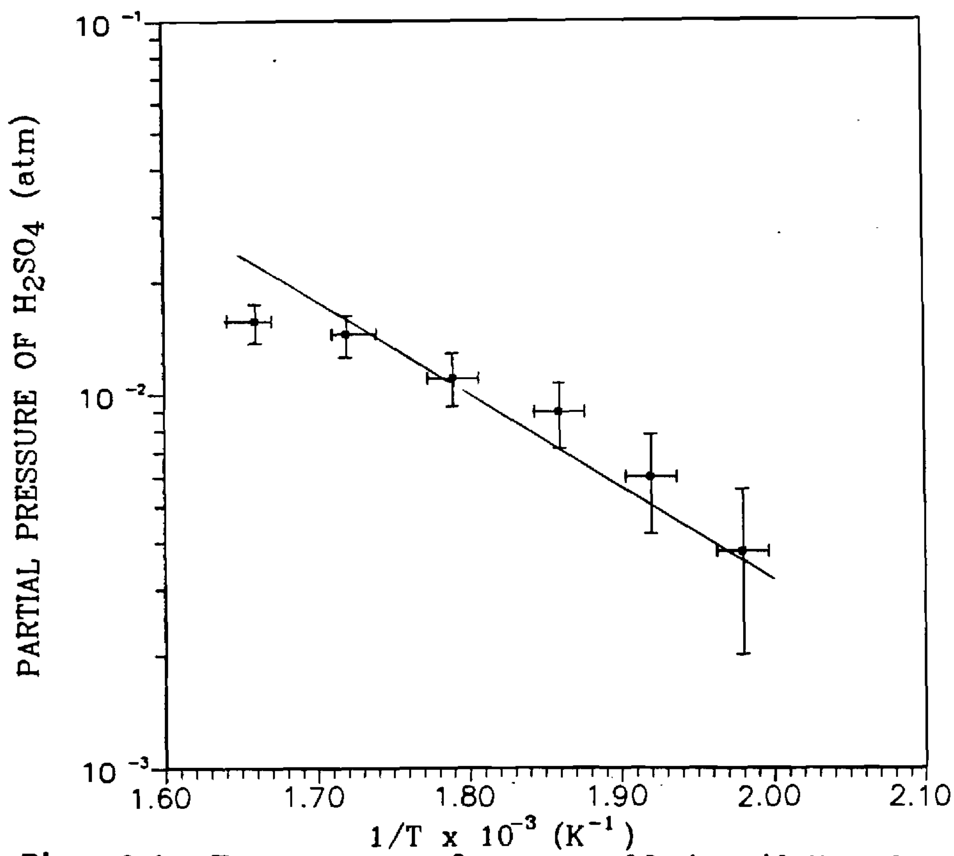


Figure 3.4 : Vapor pressure of gaseous sulfuric acid (95.9 %) as a function of temperature. the illustrated points are from laboratory measurements while the solid line represents a best-fit model. Error bars for pressure and temperature are shown.

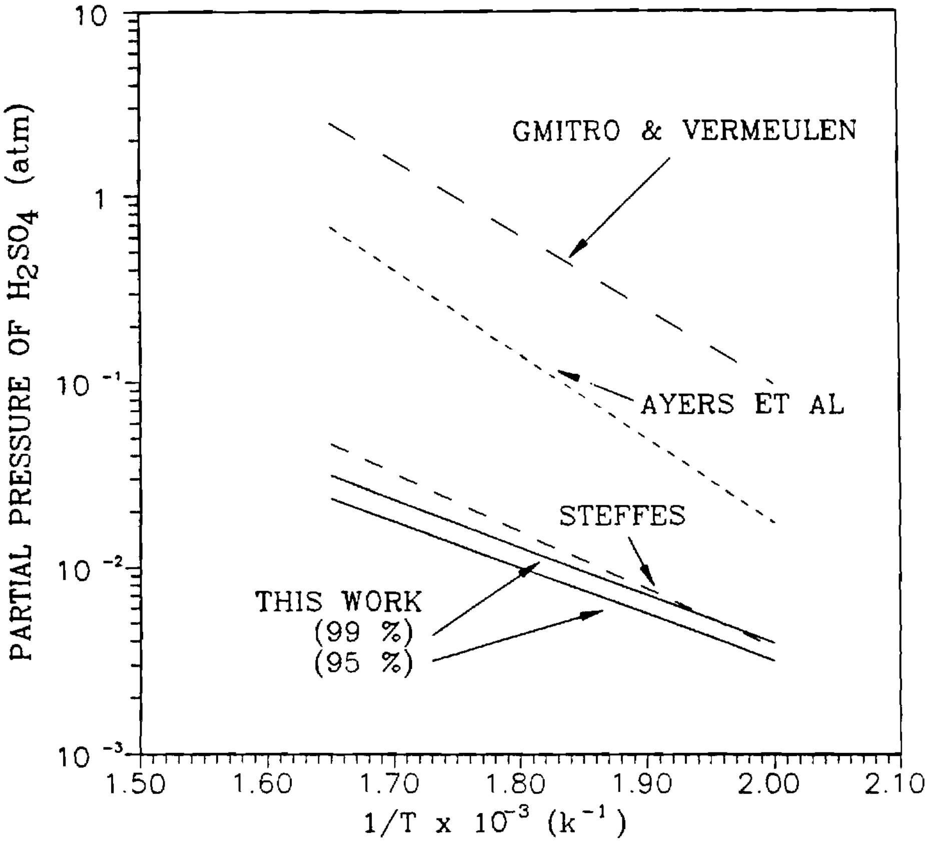


Figure 3.5 : Best-fit expression (solid line) from our measured partial pressure of sulfuric acid as a function of temperature in comparison with Steffes(1985), Ayers et. Al. (1980) and Gmitro & Vermeulen (1964).

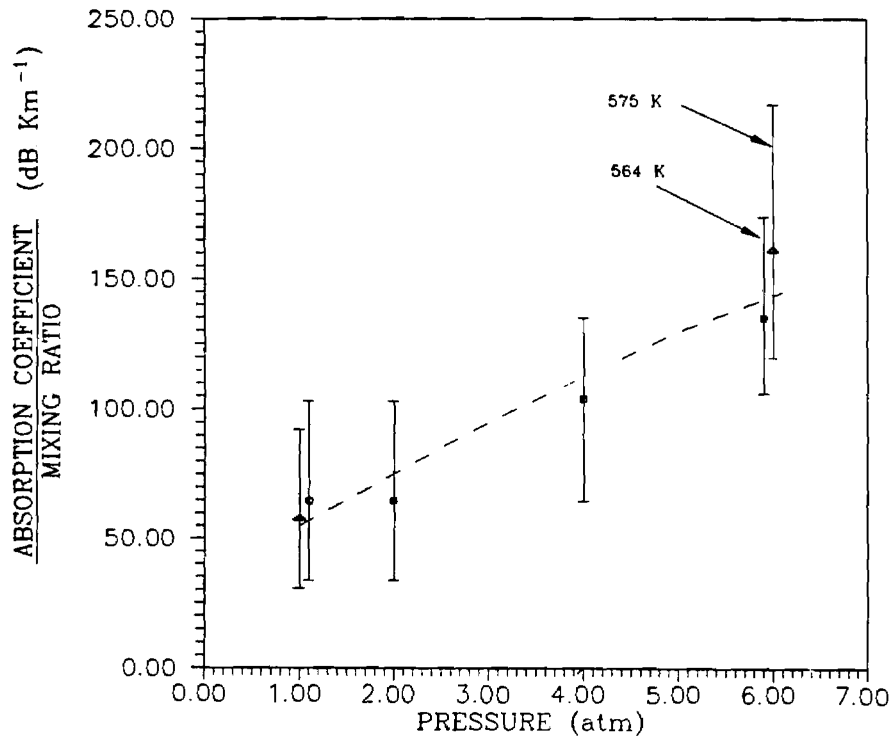


Figure #3.6 : Corrected measured dependence of the microwave absorptivity (normalized by number mixing ratio) for gaseous sulfuric acid in a CO2 atmosphere at 2.24 GHz (13.4 cm wavelength). Dashed line represents a best-fit multiplicative expression for absorptivity.

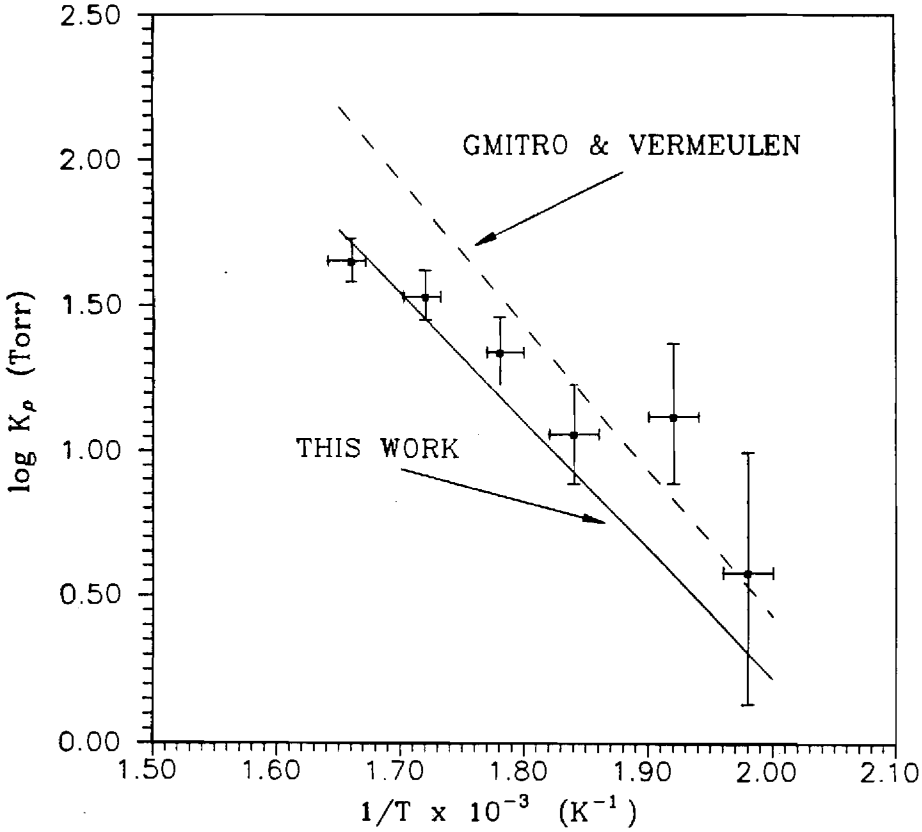


Figure 3.7 : Comparison between our best-fit expression for the equilibrium constant and the data reported by Gmitro and Vermeulen (1964). Illustrated points show the measured values of the equilibrium constant. Error bars for temperature and pressure are also shown.

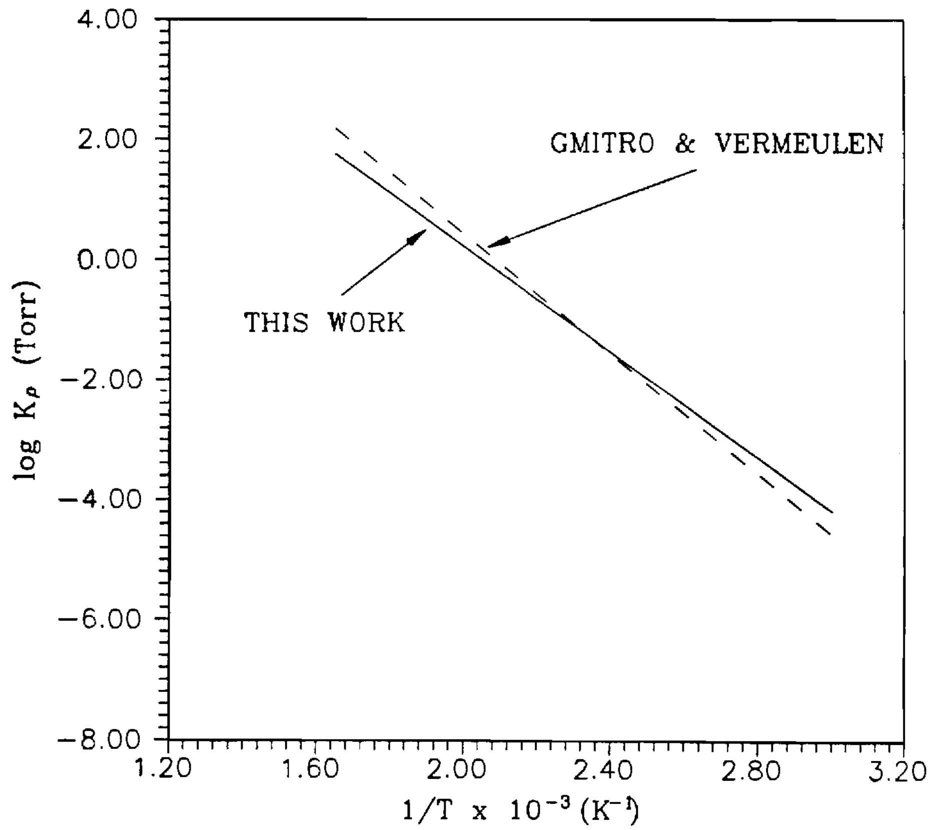


Figure 3.8 : Comparison between our best-fit expression for the equilibrium constant and the data reported by Gmitro and Vermeulen (1964).

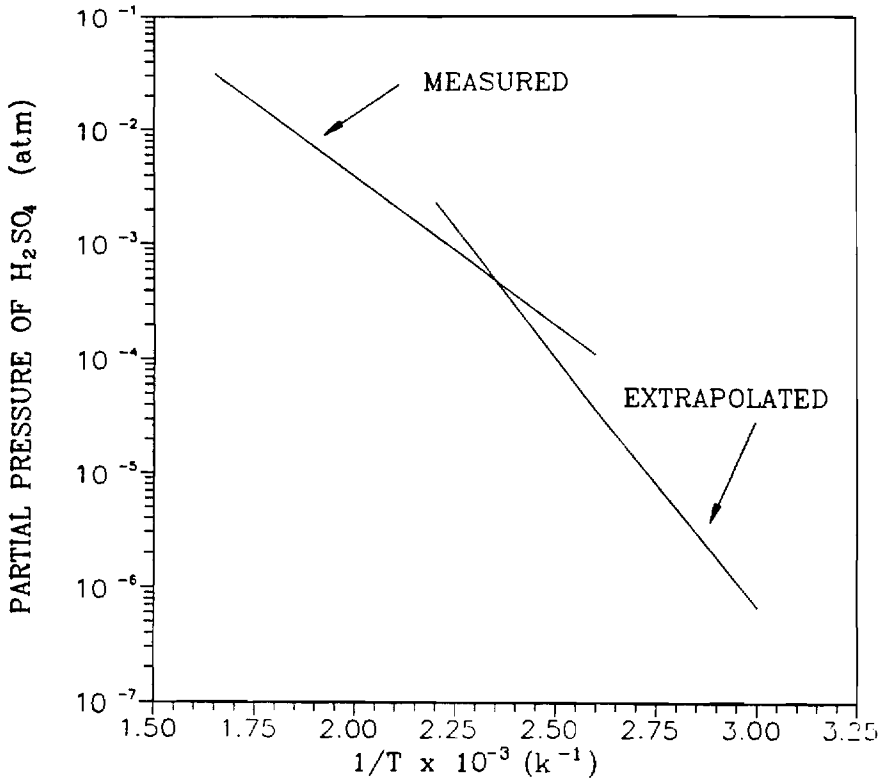


Figure 3.9 : Best-fit plot of the measured partial pressure of gaseous sulfuric acid (99 %) over a wide range of temperatures.

IV. PUBLICATIONS AND INTERACTION WITH OTHER INVESTIGATORS

In the first half of this grant year a paper regarding the observation, calibration, and interpretation of the Venus microwave emission spectrum was published in Icarus (Steffes et al., 1990. Similarly, we are currently preparing two papers for submission to Icarus on the topics of interpretation of the Jovian microwave and millimeter-wave emission spectrum (Section II) and on the vapor pressure and equilibrium between gaseous and liquid H_2SO_4 and its effect on models for the Venus atmosphere (Section III).

In early November 1989, we attended the 21st Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society and presented papers on interpretation of the Jovian microwave and millimeter-wave emission spectrum (Joiner and Steffes, 1989), on the vapor pressure and equilibrium between gaseous and liquid H_2SO_4 (Fahd and Steffes, 1989), and on the temporal variation of the abundance of SO_2 below the clouds of Venus (Steffes, 1989).

Our work has been complemented by our involvement in the Pioneer-Venus Guest Investigator Program in which we have been involved in processing radio occultation data in order to obtain 13 cm absorptivity profiles for the Venus atmosphere (Jenkins and Steffes, 1990). This has kept us in close contact with a number of Venus investigators. More informal contacts have been maintained with groups at the California Institute of Technology, with the Stanford Center for Radar Astronomy (Drs. V.R. Eshleman, G.L. Tyler, and T. Spilker, regarding Voyager results for the outer planets, and laboratory measurements), and with JPL (Drs. Robert Poynter, Samuel Gulkis, and Michael Klein, regarding radio astronomical observations of the outer planets and Venus). We have also worked with Dr. Imke de Pater (University of California-Berkeley) by using our laboratory measurements of atmospheric gases in the interpretation of radio astronomical observation of Venus and the outer planets. We have also studied possible effects of the microwave opacity of cloud layers in the outer planets' atmospheres. In this area, we have worked both with Dr. de Pater and with Dr. Paul Romani (Goddard SFC).

Dr. Steffes has also been active in the review of proposals submitted to the Planetary Atmospheres Program at NASA. We have also continued to serve the planetary community through the distribution of reprints of our articles describing our laboratory measurements and their application to microwave and millimeter-wave data from planetary atmospheres. The results of these measurements have been used in the mission planning for radio and radar systems aboard the Galileo and Magellan missions, and more recently, for proposed experiments for the Cassini mission. Another source of close interaction with other planetary atmospheres principal investigators has been Dr. Steffes' membership in the Planetary Atmospheres Management and Operations Working Group (PAMOWG). Travel support for Dr. Steffes' attendance at PAMOWG meetings, as well as the November AAS/DPS meeting, has been provided by Georgia Tech in support of Planetary Atmospheres Research.

V. CONCLUSION

In the first half of this grant year, we have continued our work with laboratory measurements and interpretation of the millimeter-wave properties of atmospheric gases contained in the outer planets. The results of our studies have been significant in that they suggest the possibility of detecting H_2S or cloud condensates at certain millimeter wavelengths. Over the next six months, we plan to continue development of our models for Jovian millimeter-wave emission. We will also begin laboratory measurements of the millimeter-wave properties of gaseous H_2S.

Our Venus studies have made it possible for us to measure the dissociation of gaseous H_2SO_4 into SO_3 and H_2O, which will aid in modeling of the Venus atmosphere, and will make it possible to correct previous laboratory measurements of the microwave opacity of gaseous H_2SO_4. We have also developed corrected expressions for the microwave opacity from gaseous H_2SO_4 which will allow a more accurate interpretation of the 13 cm absorptivity profiles provided by Pioneer-Venus radio occultation studies. In the next six months we will complete designs and begin laboratory measurement of the millimeter-wave properties of liquid H_2SO_4 and gaseous SO_2.

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Appendix A

Dual wavelength observations of the 1.4 mm Brightness of Jupiter

Proposed by

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The study of sulfur compounds on the outer planets may provide clues to the origin and evolution of the solar system as well as the coloration of the cloud formations on Jupiter (West et al, Icarus 65, 1986, pp.161-217). Thus far, the detection of sulfur bearing compounds on the outer planets has eluded planetary scientists. Ground-based observations at microwave and millimeter wavelengths provide one of the few means to probe beneath the cloud layers of the outer planets where the sulfur compounds are expected to exist.

At microwave frequencies, the dominant absorber on Jupiter and Saturn is gaseous ammonia (NH_3). Observations of the microwave emission from Jupiter can be well explained by modelling the radiative transfer of the planet using various profiles for the ammonia abundance (see e.g. dePater and Massie, Icarus 62, 1985, pp.143-171). However, when the same radiative transfer models are used to calculate the millimeter-wave emission of Jupiter, a discrepancy is found to exist between the model calculations and the existing radio astronomical observations. Figure 1 shows several model calculations along with the actual observations.

One possible explanation for this discrepancy is the existence of gaseous hydrogen sulfide (H_2S), which has several strong absorption lines at millimeter wavelengths. Hydrogen sulfide is thought to be an important constituent in the cloud formation processes of the outer planets. It is expected to combine with ammonia to form an ammonium hydrosulfide (NH_4SH) cloud layer near the 2 bar level on Jupiter. The NH_3 profiles which have been derived from microwave measurements coupled with cloud formation models predict that H_2S gas exists in vast amounts (as much as ten times the solar abundance) at or below the cloud layers.

Infrared observations by Larson et al.(Icarus 60, 1984, pp.621-639) have provided upper limits on the amount of H_2S present above the proposed NH_4SH cloud layer. These limits suggest that nearly all of the sulfur is locked up in and below the NH_4SH clouds. Millimeter-wave observations probe levels of the Jovian atmosphere at and just below the NH_4SH cloud layer. However, all of the existing observations at millimeter wavelengths have been made with relatively large bandwidths (on the order of 70 GHz), thus eliminating the possibility of detecting the smaller scale H_2S spectral features and confirming the existence of the NH_4SH cloud.

Two strong rotational lines appear in the millimeter-wave spectrum of H_2S and fall within the operating frequencies of the CSO. The center frequencies are 216.710 and 300.505 GHz and the line strengths are 2.14, and 3.01 respectively. The line at 216.7 provides the best opportunity to search for H_2S, since the rotational NH_3 lines begin to dominate the spectrum at 1 mm. Model calculations using the expected maximum and minimum vertical mixing ratios for NH_3 and H_2S are shown in Figure 2.

The difference in the brightness of the planet at the two frequencies ranges from approximately 2K worst case to 4K best case. This gives a similar differential range of 117 Jy to 233 Jy assuming a distance of 4.2 AU to Jupiter and a radius of 71,600 km with the total output from Jupiter at 10,500 Jy. The corresponding change in antenna temperature, assuming an antenna efficiency of 30%, is on the order of 1-2K. In order to achieve the maximum sensitivity, the full 500 MHz bandwidth will be needed and any smaller scale spectral information will not be needed. With this bandwidth, the needed sensitivity should be achieved. The effect of the double side band must also be considered. Since the H_2S spectral feature shown in Figure 2 is sufficiently wide due to pressure broadening (much greater than the 2.8 GHz separation), this will not affect the observation.

The most recent observations shortward of 3mm have used Mars as the primary calibrator. Its calculated millimeter-wave emission is assumed to be accurate to within 10%. Although we would ideally like to use Mars as the calibrator for our observation, the two planets will not be in a suitable position to make such an observation at any time this year. However, since we are primarily interested in the "differential" emission at two frequencies, an "absolute" measurement is not required. There are several calibrator stars which would serve as suitable calibrators depending on the time of the observation.

The proposed observation would require at least two separate observations at different frequencies on and off the peak (e.g. 216.7 GHz and 200 GHz) of the H_2S line in order to observe the "differential" emission. We propose to observe Jupiter while it is fairly close to opposition. This will occur during the first and last three or four months of the year. Assuming favorable weather conditions, the observation should require about four hours per day for three days.

A rare opportunity to make an "absolute" observation of Saturn, using Mars as the calibrator, will occur early in March when Saturn and Mars will be just a few degrees apart. Although the effects of H_2S on the Saturnian spectrum will likely not be seen, a similar differential observation at two frequencies far apart (e.g. 200 GHz and 300 GHz) would be the first such observation utilizing a small bandwidth. This type of measurement would add significantly to the poorly understood millimeter spectrum of Saturn in which ammonia plays the dominant role with the clouds and ring absorption processes at these wavelengths being poorly understood. An observation of Saturn and Mars could be made during the same time period as a measurement of Jupiter since they will occur several hours apart.

The Caltech Submillimeter Observatory (CSO) offers the unique combination of the correct frequencies and bandwidths necessary for the detection of H_2S on Jupiter. The bandwidth is large enough to provide the necessary sensitivity, while small enough to permit a dual wavelength measurement of the H_2S feature.

Figure 1

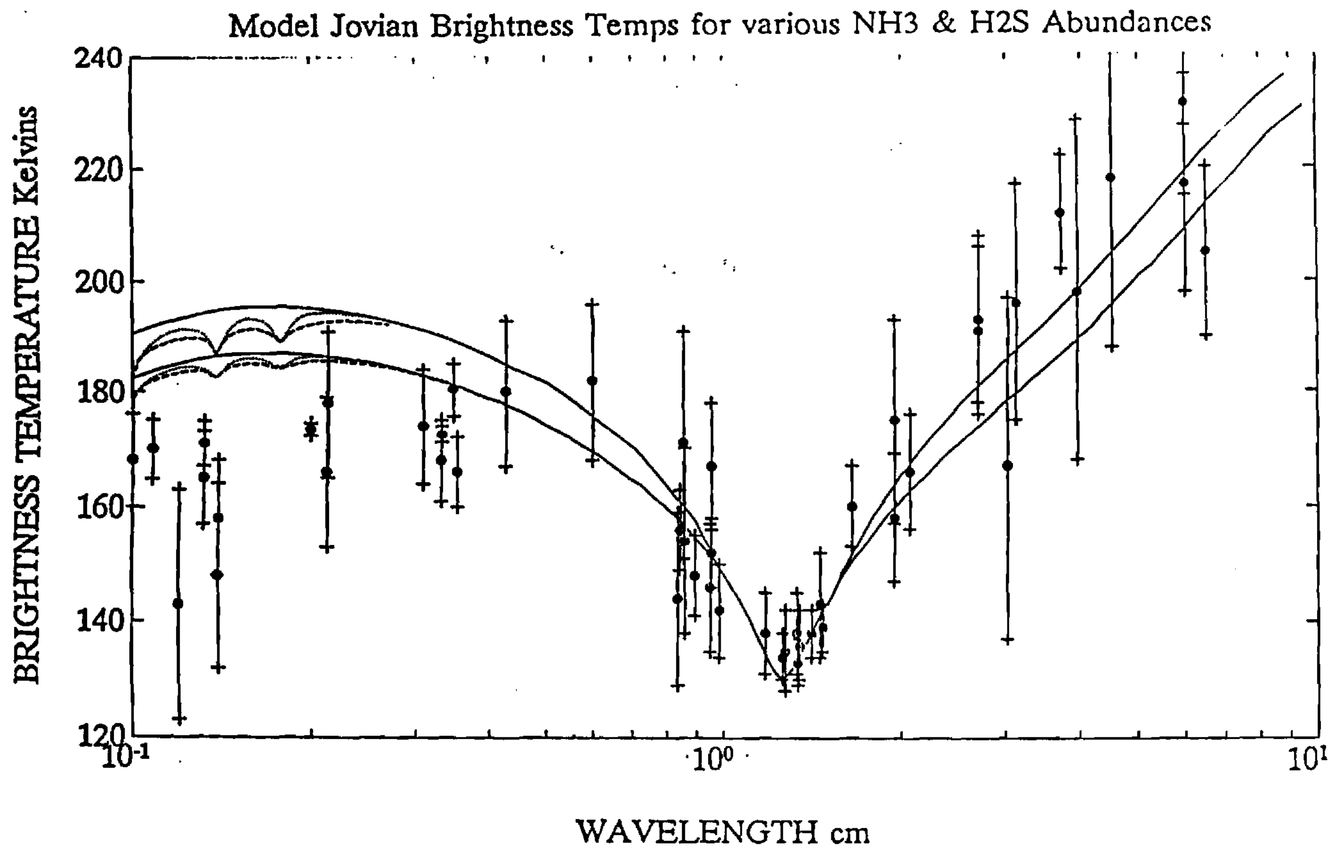
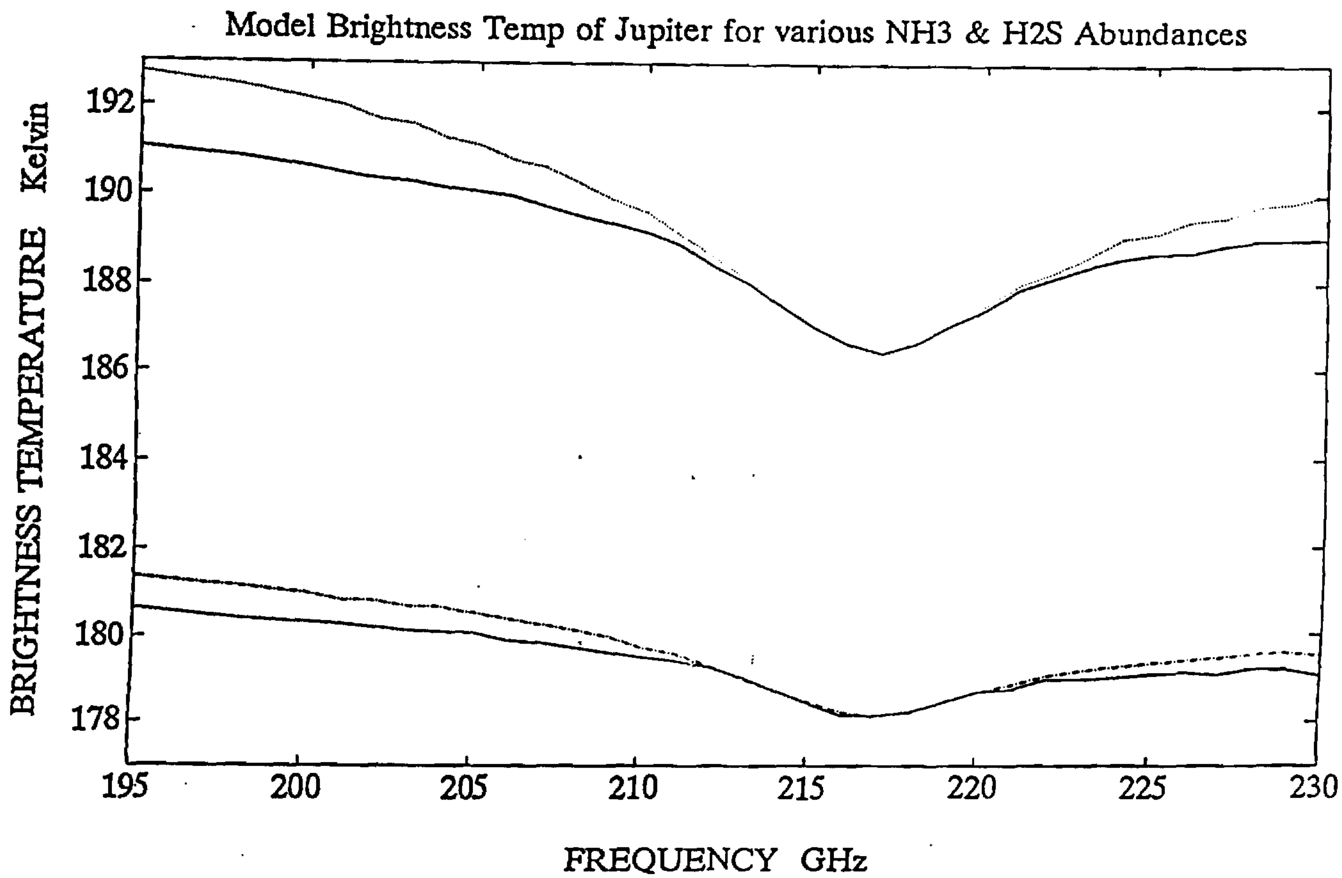


Figure 2



Appendix B

CALIFORNIA INSTITUTE OF TECHNOLOGY

GEORGE W. DOWNS LABORATORY OF PHYSICS 320-47
PASADENA, CALIFORNIA 91125

19 February 1990

Ms. Joanna Joiner
Georgia Technology
P. O. Box 34362
Atlanta, GA 30332

Dear Joanna,

Thanks for your recent proposal to use the Caltech Submillimeter Observatory. A review of proposals was held by a committee consisting of astronomers from outside Caltech. The results of that review are given below.

Proposal: 1.4 MM Brightness of Jupiter

Ratings: 3/5

We have scheduled observations for sometime in November. We will be in touch with you at a later date.

Sincerely,

Thomas G. Phillips
Director, Caltech Submillimeter Observatory

TGP:ph

RENEWAL PROPOSAL

AND

ANNUAL REPORT
(Includes Semiannual Status Report #14)

TO THE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

for

GRANT NAGW-533

LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

Paul G. Steffes, Principal Investigator

Report Period: November 1, 1989 through October 31, 1990
Proposed Renewal Period: November 1, 1990 through October 31, 1991
Requested Funding Level: $70,465

Submitted by

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July 1990

TABLE OF CONTENTS

I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing atmospheric constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studies, often leads to significant misinterpretation of available opacity data. For example, laboratory measurements performed by Joiner et al. (1989), under Grant NAGW-533, have shown that the millimeter-wave capacity of ammonia between 7.5 mm and 9.3 mm and also at the 3.2 mm wavelength is best described by a different lineshape than was previously used in theoretical predictions. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements and to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

A key activity over this past grant year has continued to be laboratory measurements of the microwave and millimeter-wave properties of the simulated atmospheres of the outer planets and their satellites. However, we have also focussed on development of a radiative transfer model of the Jovian atmosphere at wavelengths from 1 mm to 10 cm. This model utilizes our laboratory data and has also been used to evaluate the need for laboratory measurements of other possible absorbers. This modeling effort has led us to conduct a laboratory measurement of the millimeter-wave opacity of hydrogen sulfide (H_2S) under simulated Jovian conditions. Similarly, our modeling effort suggests that it may be possible to detect H_2S in the atmosphere of Jupiter using a medium resolution observation at 1.4 mm. Since no sulfur compounds have yet been detected in the Jovian atmosphere, this would be an important observation. An observation is planned for November from the Caltech Submillimeter Observatory (CSO) in Hawaii. A description of this modeling effort, the laboratory experiment, and the proposed observation is given in Section II.

Recently, we completed measurement, calibration, and interpretive studies of the Venus microwave emission, and a paper entitled, "Observations of the Microwave Emission of Venus from 1.3 to 3.6 cm," by P.G. Steffes, M.J. Klein, and J.M. Jenkins (Steffes et al., 1990) has been published in Icarus. One important issue which was discussed in this paper is the discovery that the microwave absorptivity for gaseous H_2SO_4 which was measured by Steffes (1985 and 1986) appears to differ from a theoretical spectrum newly computed by Janssen (personal communication) by a scale factor. That scale factor suggested that the theoretically-derived "dissociation factor" for gaseous H_2SO_4 (i.e., the percentage of H_2SO_4 which breaks down to form SO_3 and H_2O) may have been underestimated. This could result in an underestimation of the absorption from gaseous H_2SO_4. Therefore, an experiment has been conducted to correctly evaluate the "dissociation factor" and thus allow unambiguous calibration of laboratory data for H_2SO_4 opacity. A complete description of this experiment was given in Semiannual Status Report #13 for Grant NAGW-533 (November 1, 1989 through April 30, 1990), and has been submitted as a paper to Icarus (Fahd and Steffes, 1990).

Yet another important source of information regarding the Venus atmosphere is the increasing number of high-resolution millimeter-wavelength emission measurements which have been recently conducted. (See, for example, de Pater et al., 1990) Correlative studies of these measurements with Pioneer-Venus radio occultation measurements (Jenkins and Steffes, 1990) and out longer wavelength emission measurements (Steffes et al., 1990) should provide the necessary data for characterizing temporal and spatial variations in the abundance of gaseous H_2SO_4 and SO_4, and for modeling its role in the subcloud atmosphere. In fact, it appears from the results of Steffes et al., (1990) that long term temporal variations in subcloud SO_2 abundance may indeed be occurring. However, unambiguous results require that we have dependable knowledge of the microwave and millimeter-wave opacity of gaseous and liquid H_2SO_4, and of gaseous SO_2 under Venus conditions.

While some laboratory measurements of the microwave absorption properties of gaseous SO_2 under simulated Venus conditions were made at 13 cm and 3.6 cm wavelengths by Steffes and Eshleman (1981b), no measurements have been made at shorter wavelengths. Since the 1.35 cm wavelength appears to be one of the better wavelengths for measuring the sub-cloud SO_2 abundance (Steffes et al., 1990), we have conducted laboratory measurements of the 1.35 cm (and 13 cm) opacity of gaseous SO_2. The results and application of this work are discussed in Section III of this proposal/report.

In the next grant year we propose to measure the millimeter-wave absorptivity of both gaseous and liquid H_2SO_4 and of gaseous SO_2 under simulated Venus conditions (at the 3 mm wavelength). The system being developed for measurements of the 3 mm properties of liquid H_2SO_4 is briefly described in Section III. As described in Section II, we will also complete laboratory measurements of the 1.4 mm (216 GHz) absorptivity of hydrogen sulfide (H_2S) under simulated Jovian conditions and use the results for interpreting our November 1990 observation of Jupiter at that wavelength.

II. OUTER PLANETS STUDIES

A. Dual Wavelength Observation of Jupiter at 1.4 mm

Several different calculated emission spectra for Jupiter using various H_2S distributions for two different ammonia distributions are shown Figure 1. These emission spectra were developed using the Jovian atmospheric model which we described in Semiannual Status Report #13 for Grant NAGW-533 (November 1, 1989 - April 30, 1990). An expanded view of the line at 216 GHz is shown in Figure 2. The spectra show that detection of H_2S is possible using a small bandwidth (on the order of 1 GHz or less) receiver. At least three radio telescopes with such receivers exist:

- The Caltech Submillimeter Observatory (CSO) at Mauna Kea, Hawaii

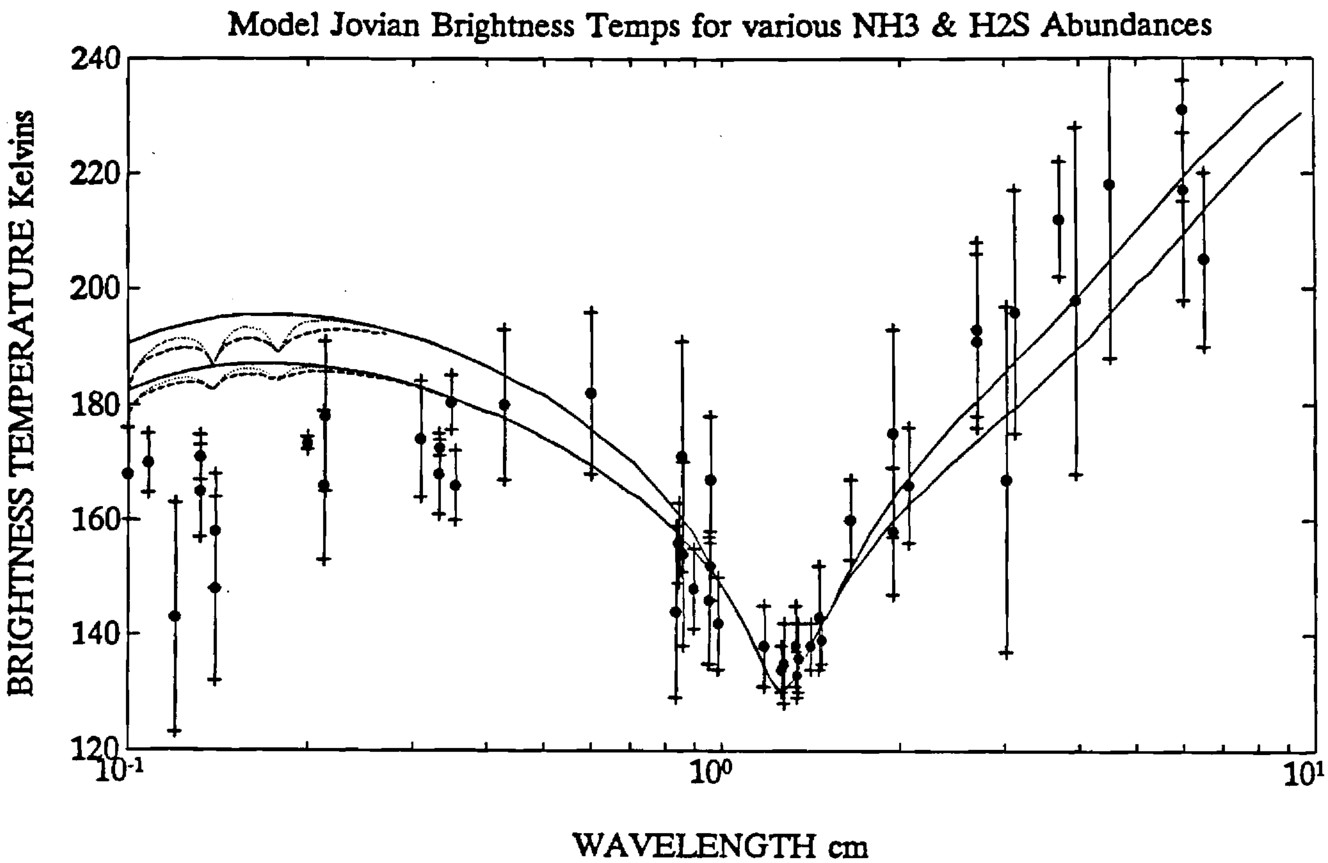

Figure 1 : Calculated emission spectra for Jupiter using two different NH_3 abundance profiles with no H_2S, solar abundance H_2S, and ten times solar abundance H_2S.

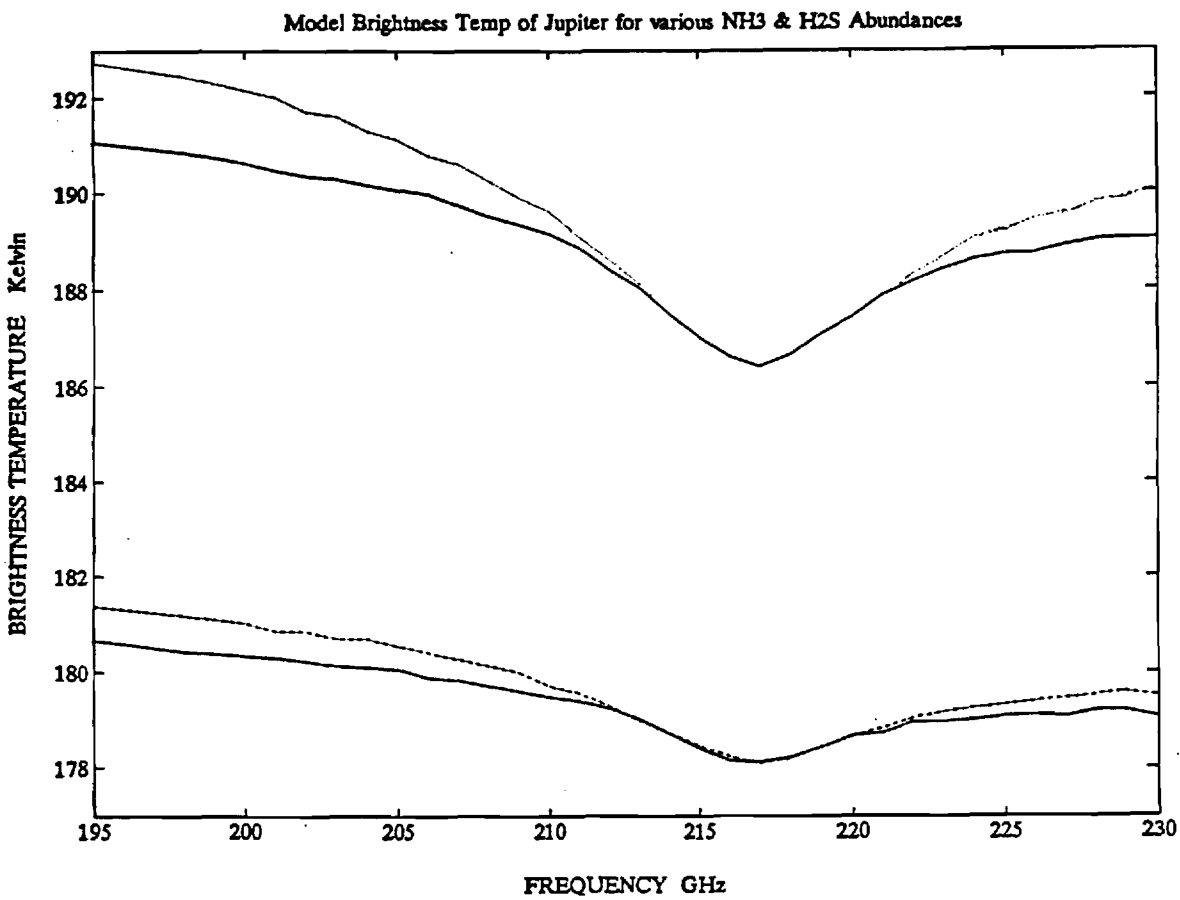

Figure 2: Expanded view of calculated emission at the 216 GHz absorption line of H_2S.

- The University of Massachusetts Millimeter Observatory

- The NRAO Observatory at Kitt Peak, Arizona

Of the three observatories capable of making a small bandwidth observation at 216 GHz, the CSO receiver is the most sensitive (by a factor of two or more). The CSO also provides the best location for making such an observation. The high altitude at Mauna Kea minimizes the effects of absorption from the earth's atmosphere. However, since the dip in emission due to H_2S is small, calculations must be made to see if the antenna and receiver are capable of measuring the dip.

The first step is to calculate the change in antenna temperature which will result from the expected 2K dip in the Jovian emission which is due to H_2S. It will be useful to first define several quantities used in this type of calculation. The Rayleigh-Jeans approximation, which is valid when ($h\nu \ll kT$) is commonly used at radio frequencies in order to simplify Planck's law. This approximation to Planck's law is given by

$$B = 2\nu^2 kT/c^2 = 2kT/\lambda^2. \tag{1}$$

This approximation produces errors on the order of 10% at millimeter wavelengths. Using the Rayleigh-Jeans approximation, the total spectral power density, S, radiated from a spheric blackbody of radius r at a distance d from the source is given as

$$S = \pi kT(r/d)^2/\lambda \tag{2}$$

(Gulkis, 1987), where S is the flux density. The flux density is in units of power per unit surface area per unit frequency. A commonly used unit for flux density is the Jansky(jy) which is defined as 10^{25} W m^{-2} Hz^{-1}. The change in antenna temperature, ΔT, (in Kelvins) due to a certain flux density, S, may be calculated using

$$\Delta T = \frac{S}{2K} \cdot A_{eff} \tag{3}$$

where A_{eff} is the effective area of the antenna. The effective area is defined as

$$A_{eff} = \sigma \cdot \pi r^2 \tag{4}$$

where σ is the efficiency of the dish and r is the radius of the dish. The factor of two in the denominator of Equation 3 is due to the fact that only one polarization is observed.

The ΔT_{H_2S} from Jupiter (change in antenna temperature due to the dip in emission from the H_2S) can be calculated using Equations 2-4. For Jupiter, $r \simeq 71.6 \cdot 10^3$ km and $d \simeq 4.2$A U (astronomical units) or $6.28 \cdot 10^8$ km. The diameter of the CSO is 10.4 m and an efficiency of 30% was assumed. The difference in emission assuming a temperature of 180K at 216 GHz and a temperature of 182K at 200 GHz was calculated. After subtracting out the difference in flux due to the difference in wavelength, the ΔT_{H_2S} was found to be 0.76 K.

The sensitivity of the receiver, ΔT_{rms}, must now be examined in order to determine whether or not it is capable of measuring the ΔT_{H_2S}. The sensitivity equation of an ideal receiver is given as

$$\Delta T_{rms} = 2 \cdot \frac{T_s}{\sqrt{t\ d\nu}} \tag{5}$$

where ΔT_{rms} is called the rms noise power and T_s (in units of Kelvins) is defined as the system temperature and is a measure of the noise power from the receiver, t is the integration time in seconds, and $d\nu$ is the bandwidth of the receiver in Hz. The factor of two accounts for the fact that the CSO is a double side band (DSB) receiver. The full receiver bandwidth of the CSO is 500 MHz and operates between 200 and 260 GHz. Although the CSO is equipped to make observations with much greater resolution, the full bandwidth of the receiver will be utilized in order to achieve the necessary sensitivity.

The noise temperature of the CSO (for double side band) is around 100K and the system sensitivity is about 500 mJy for a one second integration time. Evaluating Equation 5 gives a ΔT_{rms} of about 0.01 K. Since this is much smaller than the 0.76 change in emission which is due to H_2S, the CSO should provide the needed sensitivity in order to detect the H_2S feature.

A proposal was written to the CSO and has been accepted. Three nights of observing time in November 1990 have been granted for use of the CSO.

B. Laboratory Measurement of Hydrogen Sulfide Absorption

Our current method for computing of the millimeter-wave absorption from H_2S uses a Van Vleck-Weisskopf formalism for the pressure-broadened lineshape. However, as in the case of ammonia, the actual absorption at higher pressures may be significantly different from the Van Vleck-Weisskopf theory. In addition, the linewidths for this molecule have never been measured. These parameters must be known accurately if reliable information is to be inferred from observing the effects of H_2S on the Jovian emission spectrum.

Our analysis shows that by using higher concentrations of H_2S in a hydrogen-helium atmosphere, absorption should be detectable in the laboratory. However, the absorption lines of H_2S occur at much higher frequencies (168, 216, and 300 GHz) than our previous laboratory experiments. Thus, the signal source used at these frequencies would have to be harmonically generated. The use of a frequency doubler in order to achieve harmonic generation would decrease the signal strength. The signal-to-noise ratio would therefore be lower than that of previous experiments. Since H_2S is extremely opaque near the line centers, it may be possible to measure its absorptivity using a long glass cell with a source and precision attenuator at one end and a detector at the other. This configuration is shown in Figure 3. This type of configuration would greatly simplify the laboratory measurement since a resonator would not be necessary.

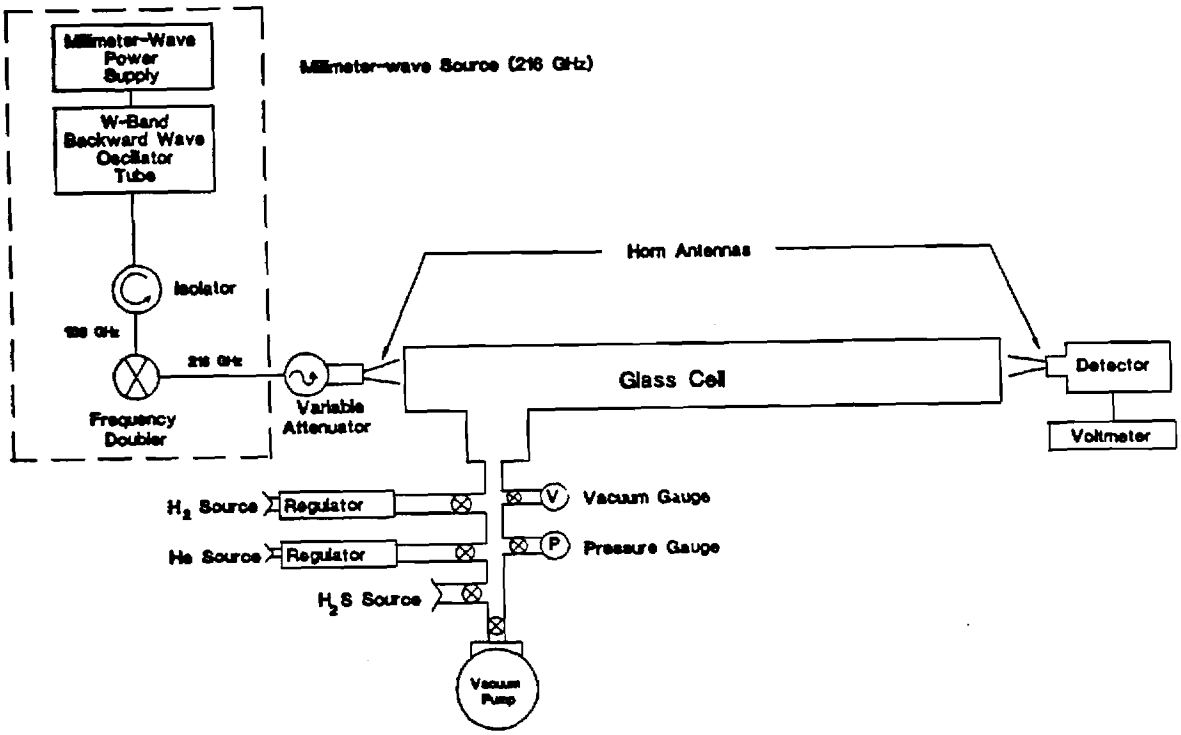

Figure 3: Block diagram of laboratory configuration for measuring H_2S absorption.

Some of the equipment, such as the signal source, horn antennas, and waveguides will be supplied by the Georgia Tech Research Institute (GTRI). This experiment will be conducted at room temperature since the equipment is too large to fit in our ultra-low temperature freezer. This laboratory data will be very important in analyzing the planned November 1990 observation of Jupiter in which a dip in the emission spectrum due to the 216 GHz line of H_2S will be searched for.

III. VENUS STUDIES

A. Laboratory Measurement of the 1.3 cm and 13.3 cm Opacity of SO_2 Under Simulated Venus Conditions

In our paper, "Observations of the Microwave Emission of Venus from 1.3 to 3.6 cm," (Steffes et al., 1990), we discussed the fact that the only gas which substantially affects the microwave emission from Venus at the 1.35 cm wavelength (besides CO_2) is SO_2. This is due to the relatively low opacity of gaseous H_2SO_4 at that wavelength and the relatively low abundance of gaseous H_2O present in the middle atmosphere. Since the CO_2 abundance and temperature-pressure profile in the lower and middle atmosphere do not vary significantly with time, it is possible to infer variations in the SO_2 abundance from variations in the 1.35 cm flux. However, once an accurate estimate of disk brightness is obtained, accurate estimates of SO_2 abundance can only be made if the microwave absorbing properties of SO_2 at that wavelength are well understood. While some laboratory measurements of the microwave absorption properties of gaseous SO_2 under simulated Venus conditions were made at 13 cm and 3.6 cm (Steffes and Eshleman, 1981b), no measurements have been made at 1.35 cm. Thus, we have conducted such a laboratory measurement at 1.35 cm.

The experimental approach used to measure the microwave absorptivity of gaseous SO_2 in a CO_2 atmosphere is similar to that used previously by Steffes (1986) for characterizing the absorption of H_2SO_4 in a CO_2 atmosphere. The absorptivity is measured by observing the effects of the test gas mixture on the quality factors (Q's) of microwave resonances between 2.2 and 22 GHz of two cavity resonators (see Figure 4). For relatively low-loss gas mixtures, the relation between the absorptivity of the gas mixture and its effect on the Q and the transmissivity (t) of a particular resonance is given by the equation:

$$\alpha = [Q_L^{-1}(1-t^{-1/2})-Q_C^{-1}]\ \frac{\pi}{\lambda} \tag{6}$$

where α is absorptivity of the gas mixture in Nepers km^{-1}. (Note: an attentuation constant, or absorption coefficient or absorptivity of 1 Neper km^{-1} = 2 optical depths per km (or km^{-1}) = 8.6866 dB $km^{-=1}$, where the first notation is the natural form used in electrical engineering, the second is the prevalent form used in physics and astronomy, and the third is the common (logarithmic) form. The third form is used often in order to avoid a possible factor-of-two ambiguity in meaning.) Q_L is the quality factor of the resonance when the test gas mixture is present, Q_C is the quality factor of the resonance in a vacuum, t is the transmissivity of the resonance with the gas mixture present, and λ is the wavelength (in km) of the test signal when the gas mixture is present. (Note that this new expression takes into account the effects of the coupling of the

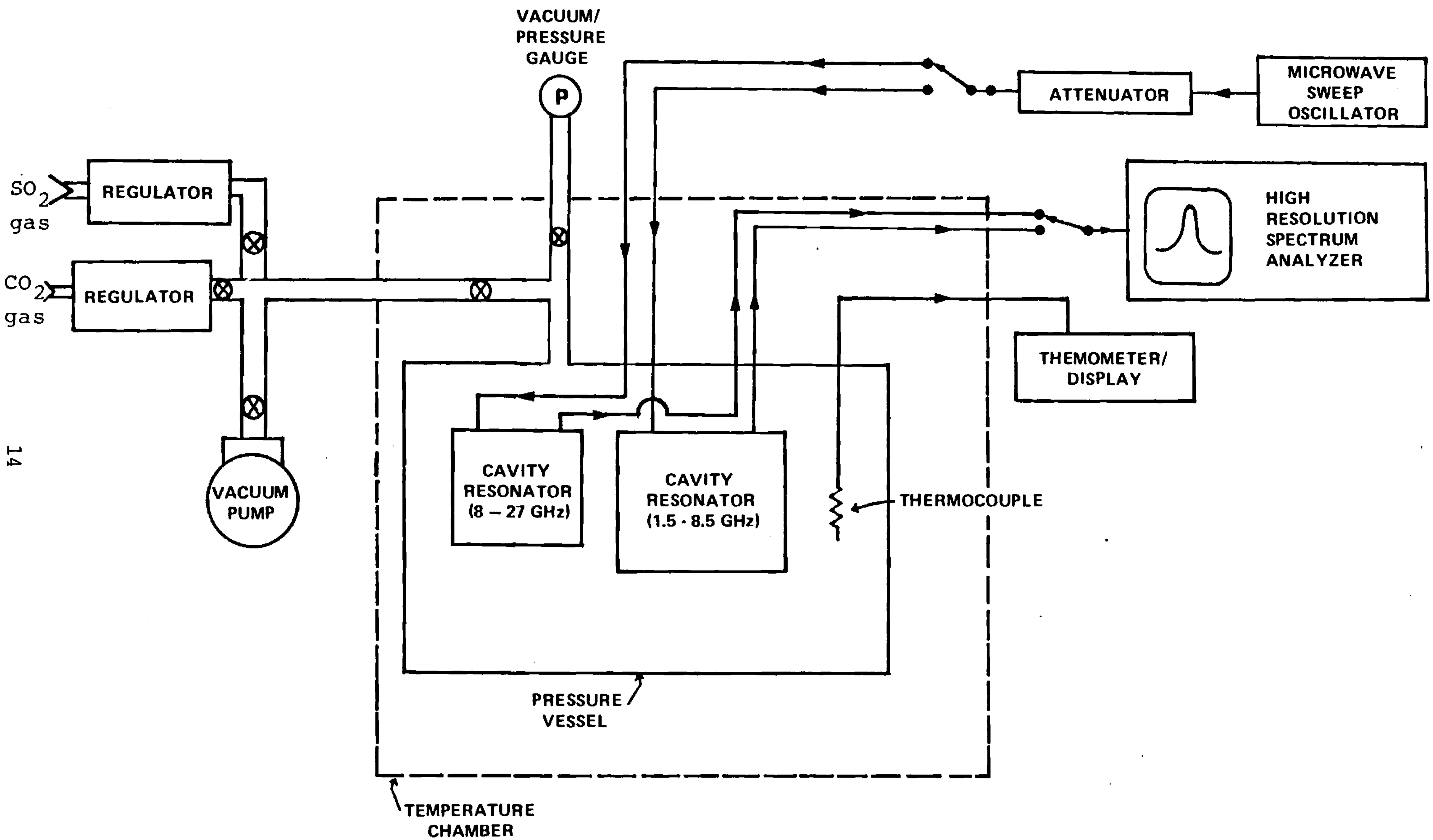

Figure 4: Block diagram of Georgia Tech Planetary Atmospheres Simulator, as configured for measurements of microwave refraction and absorption of gases under simulated Venus conditions.

resonator on the resulting absorptivity measurement. We describe this effect, known as "dielectric loading," in Joiner et al., (1989).

This experiment was conducted by introducing a mixture of 8.3% SO_2 (by volume) and 91.7% CO_2 into the pressure vessel at room temperature. The Q and the transmissivity ($0 < t < 1$) of the two resonances (one at 2.24 GHz or 13.4 cm, and one at 21.7 GHz or 1.38 cm wavelength) are measured with the spectrum analyzer (Q is simply the ratio of resonance center frequency to resonance half-power bandwidth). The measurements were made at 1 Bar pressure increments with the total pressure ranging from 1 to 6 Bars. After the quality factors measured with the gas mixture present were compared with those measured in a vacuum, the absorptivity of the gas mixture was determined as per equation (6).

The results of these measurements are shown in Figure 5 and 6. In Figure 5, we plot the measured absorptivity of SO_2 in a CO_2 atmosphere (normalized by volume mixing ratio) at 2.24 GHz. For comparison, we also plot the absorptivity computed theoretically using the Van Vleck-Weisskopf formalism as per Steffes and Eshleman (1981a). In Figure 6, we plot the measured, normalized absorptivity at 21.7 GHz along with that computed using the Van Vleck-Weisskopf formalism. Our results at 2.24 GHz (13.4 cm) are consistent with results from Steffes and Eshleman (1981b) in that the measured opacity has been shown to be at least 50% larger than computed using the Van Vleck-Weisskopf formalism. Similarly, a pressure dependence of approximately $p^{1.3}$ was found. However, at 21.7 GHz (1.38 cm) the results are quite consistent with the Van Vleck-Weisskopf formalism, except at the highest pressure (6 Bars). This result is extremely important in that it shows that the f^2 dependence of the SO_2 opacity which was proposed by

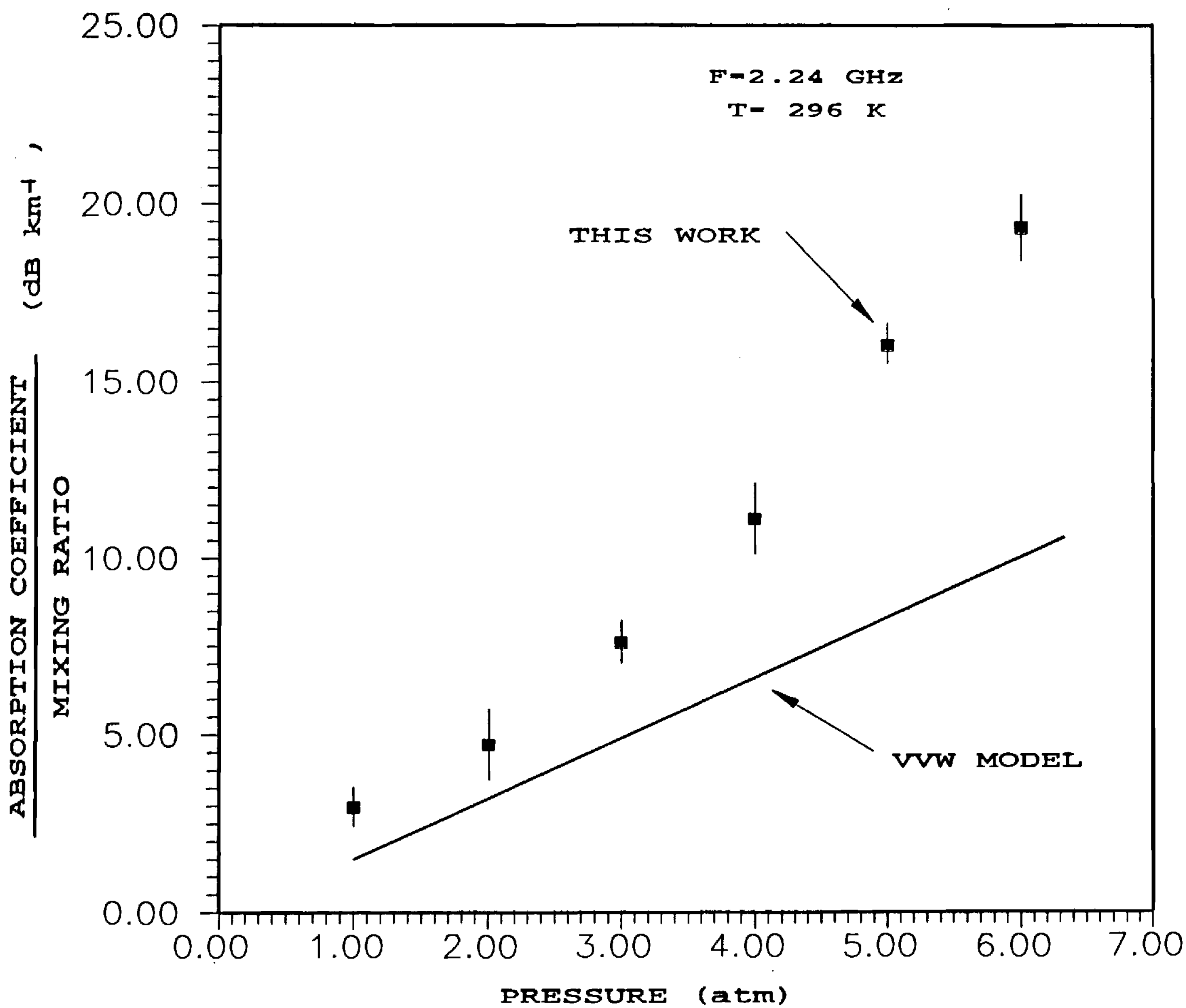

Figure 5:
Measured absorption coefficient (normalized by mixing ratio) at 2.24 GHz of SO_2 in a CO_2 atmosphere compared with theoretical calculation using the Van Vleck-Weisskopf model (solid line). Error bars shown indicate a ±1 σ about the mean value of the measured data. Measurements were made at 296 K with a 8.33% mixing ratio.

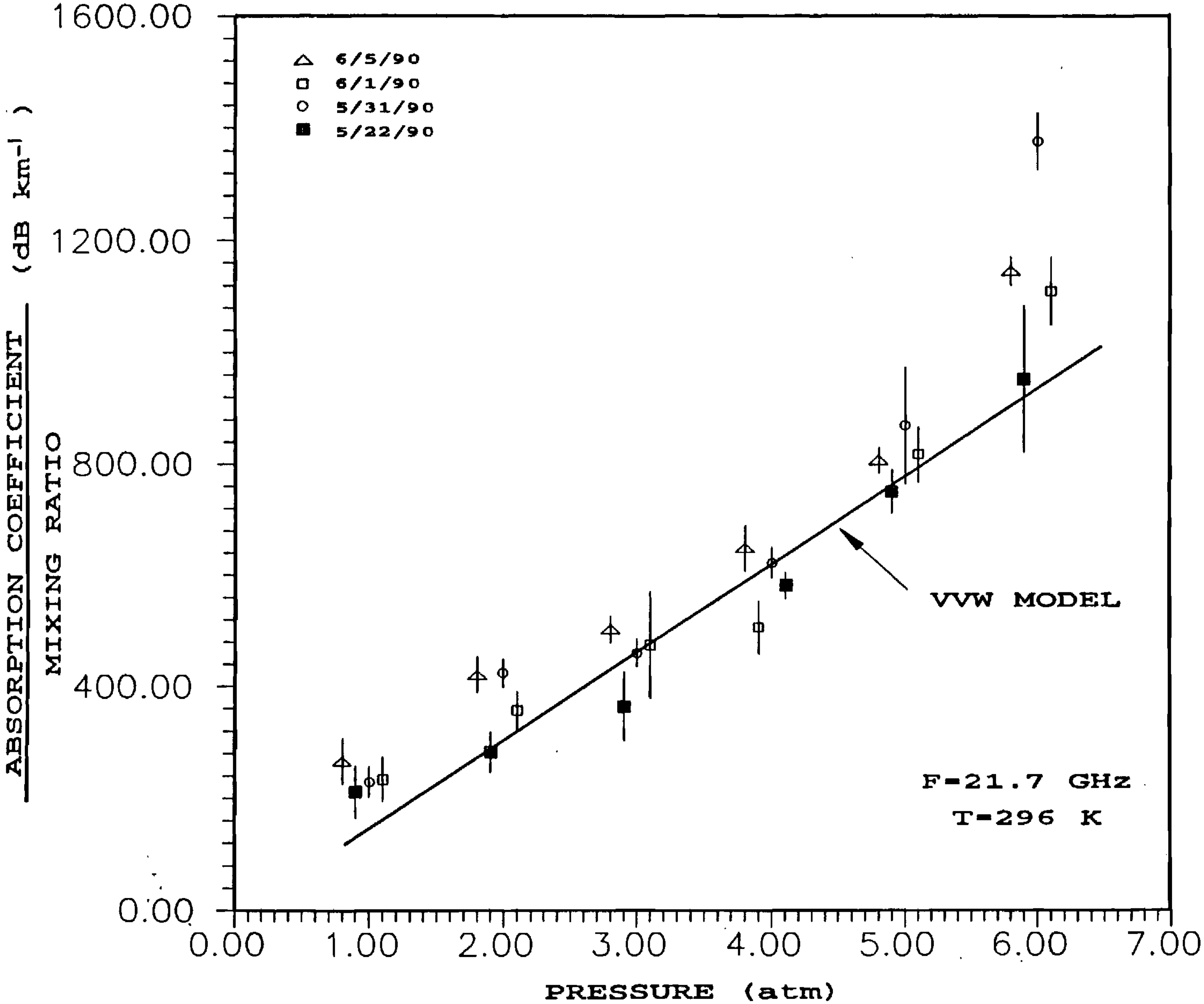

Figure 6:
Measured absorption coefficient (normalized by mixing ratio) at 21.7 GHz of SO_2 in a CO_2 atmosphere compared with theoretical calculation using the Van Vleck-Weisskopf model (solid line). Error bars shown indicate a ±1 σ about the mean value of the measured data. Measurements were made at 296 K with a 8.33% mixing ratio.

Janssen and Poynter (1981) and adopted by Steffes and Eshleman (1981b) for frequencies below 100 GHz and pressures greater than 1 Bar is not valid. Since the Van Vleck-Weisskopf formulation is valid at 1.3 cm for pressures less than 6 Bars, it is possible to use it in determining estimated SO_2 abundances from 1.3 cm emission measurements. However, since the 1.3 cm opacity appears to be lower than indicated by the expression presented in Steffes and Eshleman (1981b) it is more difficult to accurately determine limits to SO_2 abundance. For example the SO_2 abundance inferred by Steffes et al., (1990) from 1.35 cm emission was 45 (+90 or -45) ppm using the expression from Steffes and Eshleman (1981b). Using these laboratory results, the inferred abundance is about 90 (+180 or =90) ppm.

B. Laboratory Measurement of the Millimeter-Wave Properties of Liquid Sulfuric Acid

Observations of the millimeter-wave emission of Venus at 115 GHz (2.6 mm) suggests significant spatial and possible diurnal variations in the continuum flux emission (de Pater et al., 1990). Such variations are undoubtedly due to variabilities in abundances of absorbing constituents, since substantive variations in temperature-pressure profiles in the middle and lower atmosphere have not been indicated by either in-situ or radio occultation studies. Potential constituents whose abundance variability might account for the flux variations include gaseous H_2SO_4 and SO_2, and liquid H_2SO_4 (the cloud condensate). Estimating the absorbing properties of any of these constituents at frequencies near 100 GHz is difficult since no laboratory measurements have been reported for Venus-like conditions. de Pater et al. (1990) predicted that the cloud condensate was most likely the major source of non-CO_2 opacity, basing their estimate on the millimeter-wave opacity of water. However, since the microwave properties of water are substantially different from sulfuric acid (ref. Ho and Hall, in Cimino, 1982), a laboratory measurement is definitely needed.

In the next grant year, we will measure the absorption and refraction of liquid H_2SO_4 (85%, solution by weight) at 100 GHz, using the free space measurement system shown in Figure 7. Note that the complex permittivity of the sample will be measured using a millimeter-wave network analyzer. In the next grant year we will also complete construction of our laboratory system for measurement of the 3 mm opacity of gaseous H_2SO_4 and SO_4 under simulated Venus conditions.

IV. PUBLICATIONS AND INTERACTION WITH OTHER INVESTIGATORS

In this grant year, a paper regarding the observation, calibration, and interpretation of the Venus microwave emission spectrum was published in Icarus (Steffes et al., 1990). Similarly, we have submitted a paper to Icarus on the topic of the vapor pressure and equilibrium between gaseous and liquid H_2SO_4 and its effect on models for the Venus atmosphere (Fahd and Steffes, 1990). We are also preparing papers on the topic of interpretation of the Jovian microwave and millimeter-wave emission spectrum and on our laboratory measurement of the 1.35 cm opacity of SO_2.

In early November 1989, we attended the 21st Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society and presented papers on interpretation of the Jovian microwave and millimeter-wave emission spectrum

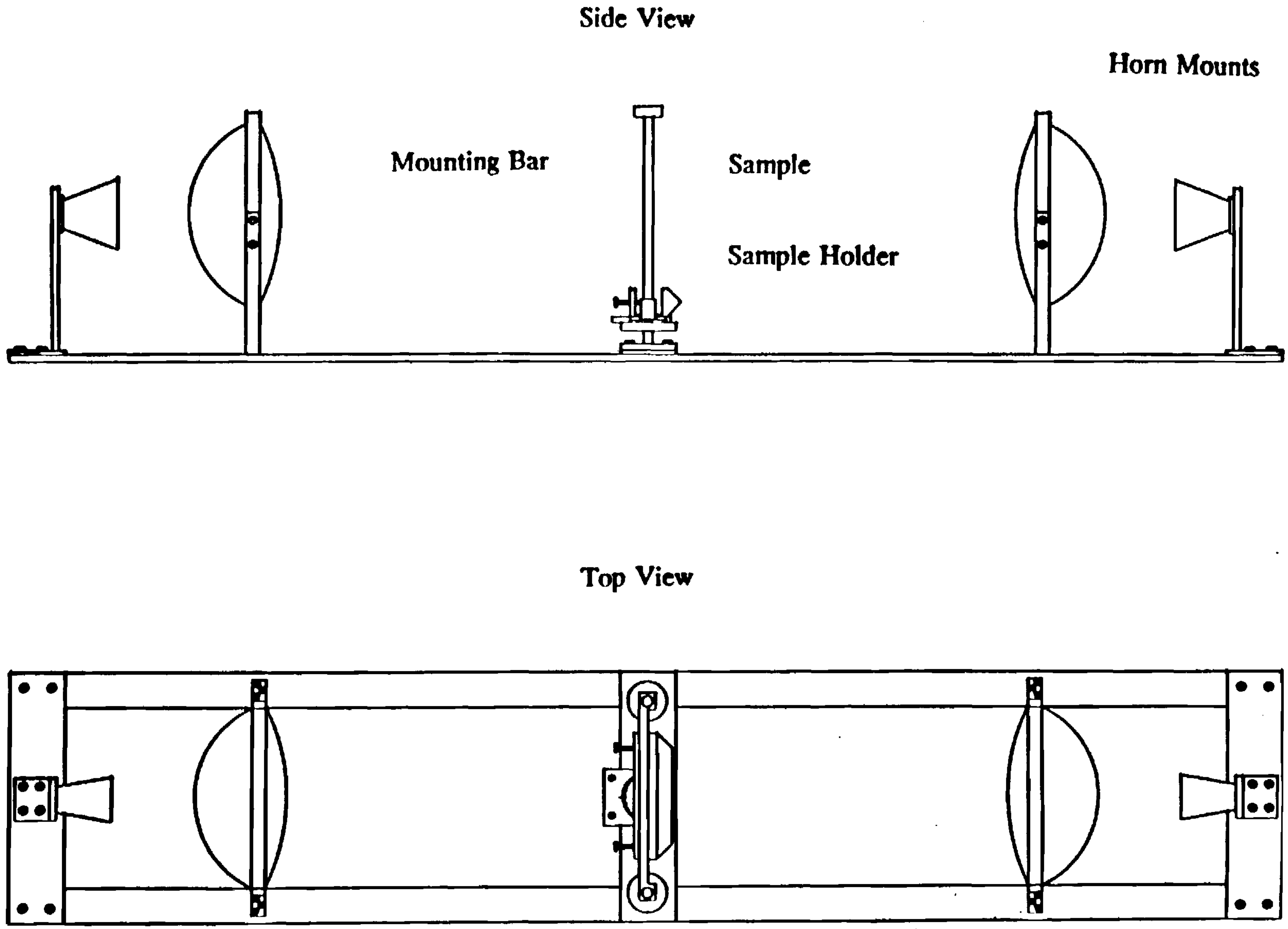

Figure 7: Sketch of free-space measurement system.

(Joiner and Steffes, 1989), on the vapor pressure and equilibrium between gaseous and liquid H_2SO_4 (Fahd and Steffes, 1989), and on the temporal variation of the abundance of SO_2 below the clouds of Venus (Steffes, 1989). Likewise, we are currently preparing papers for presentation at the October 1990 AAS/DPS meeting and accompanying Conference on Laboratory Research for Planetary Atmospheres (Charlottesville, VA).

Our work has been complemented by our involvement in the Pioneer-Venus Guest Investigator Program in which we have been involved in processing radio occultation data in order to obtain 13 cm absorptivity profiles for the Venus atmosphere (Jenkins and Steffes, 1990). This has kept us in close contact with a large number of Venus investigators. More informal contacts have been maintained with groups at the California Institute of Technology, with the Stanford Center for Radar Astronomy (Drs. V.R. Eshleman, G.L. Tyler, and T. Spilker, regarding Voyager results for the outer planets, and laboratory measurements), and with JPL (Drs. Robert Poynter, Samuel Gulkis, and Michael Klein, regarding radio astronomical observations of the outer planets and Venus). We have also worked with Dr. Imke de Pater (University of California-Berkeley) by using our laboratory measurements of atmospheric gases in the interpretation of radio astronomical observation of Venus and the outer planets. We have also studied possible effects of the microwave opacity of cloud layers in the outer planets' atmospheres. In this area, we have worked both with Dr. de Pater and with Dr. Paul Romani (Goddard SFC).

Dr. Steffes has also been active in the review of proposals submitted to the Planetary Atmospheres Program at NASA. We have also continued to serve the planetary community through the distribution of reprints of our articles describing our laboratory measurements and their application to microwave and millimeter-wave data from planetary atmospheres. The results of these measurements have been used in the mission planning for radio and radar systems about the Galileo and Magellan missions, and more recently, for proposed experiments for the Cassini mission. Another source of close interaction with other planetary atmospheres principal investigators has been Dr. Steffes' membership in the Planetary Atmospheres Management and Operations Working Group (PAMOWG). Travel support for Dr. Steffes' attendance at PAMOWG meetings, as well as the AAS/DPS meetings has been provided by Georgia Tech in support of Planetary Atmospheres Research.

V. PROPOSED PROCEDURE AND LEVEL OF EFFORT

The proposed program will continue an ambitious effort to resolve many of the uncertainties involved in the interpretation of microwave and millimeter-wave absorptivity data from Venus, Jupiter, Saturn, Uranus, and Neptune. The next grant year (November 1, 1990 through October 31, 1991) will begin with our completion of laboratory measurements of the millimeter-wave opacity of gaseous H_2S (under Jovian conditions) and liquid H_2SO_4 (Venus cloud constituent). We will use these results in completing development of microwave and millimeter-wave radiative transfer models for Venus and the outer planets. We will also observe the emission from Jupiter at and around the 1.4 mm wavelength from the Caltech Submillimeter Observatory (CSO-Mauna Kea, Hawaii) in order to set limits on the abundance of H_2S in the Jovian atmosphere. Finally, we will complete design and construction and begin operation of our system for measuring the 3 mm opacity of gaseous H_2SO_4 and SO_2.

The proposed level of effort in the 12 month period proposed for FY 91 (November 1, 1990 through October 31, 1991) involves one professor (P.G. Steffes, Associate Professor of Electrical Engineering) at 15% time, one graduate student (Graduate Research Assistant, Joanna Joiner) at 50% time, and a second graduate student (Graduate Research Assistant, Antoine K. Fahd) assistant at 50% time, with supplies and other support as indicated in the attached cost breakdown (see Section VIII). Note that we are only requesting 33% support for Ms. Joiner, with the remainder being provided by the Georgia Institute of Technology Space Grant College/Consortium. In addition to the participation in the program by Professor Steffes and the paid graduate research assistants, contributions to the program from both graduate and undergraduate students working on special projects for academic credit have been substantial. Topics of these projects have included both laboratory measurements and the application and analysis of microwave refractivity and absorptivity data from simulated planetary atmospheres, in addition to repair of laboratory microwave equipment supporting the project. We expect such contributions to continue in the future. Likewise, in the spirit of the NASA Graduate Student Researchers Program (Underrepresented Minority Focus), we continue to seek out talented underrepresented minority students and involve them in our program.

VI. FACILITIES

The School of Electrical Engineering of the Georgia Institute of Technology has extensive physical facilities devoted to a wide variety of research and development problems. The large faculty and staff conduct teaching, research, and applied research in almost every area of electrical engineering, including microwave and millimeter-wave propagation. In addition to the School itself, the facilities of the Georgia Tech Research Institute (GTRI), a world-renown organization in the area of microwave/millimeter-wave propagation and systems, are also available. Finally, the facilities of the Atmospheric Sciences Program of the School of Earth and Atmospheric Sciences at Georgia Tech are also available in this area. Overall, the ability to perform the proposed research at the Georgia Institute of Technology is excellent.

The specific measurements described in this proposal will be conducted at the Radio Astronomy and Propagation Laboratory and the accompanying Remote Sensing Laboratory, which are located within the School of Electrical Engineering. A description of the equipment being used for these measurements is given in Sections II and III.

For support of any required data analysis and computing activities, a wide range of computing services for education, research, and administration is provided by the Georgia Tech Office of Computing Services. In addition to the large institutional mainframe computers (UNIX-based CYBER 18/855 and IBM 4381), we have been furnished with an Apollo DN4500/DN3500 three-node workstation network. This network, which resides in the Remote Sensing Laboratory in the School of

Electrical Engineering, has a processing power of over 2 Megaflops, storage capability, floppy disk, and 1/2-inch magnetic tape drives, and it will have network interfaces. Numerous personal computers are also available to support this project.

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VIII. PROJECTED BUDGET

For the period of November 1, 1990 through October 31, 1991

Estimated Cost Breakdown

I.	DIRECT SALARIES AND WAGES*:			$35,818
	A.	Principal Investigator P.G. Steffes 15% time, calendar year	$10,818	
	B.	1 Graduate Student (A.K. Fahd) 50% time, calendar year	$15,000	
	C.	1 Graduate Student (J. Joiner) 33% time, calendar year	$10,000	
II.	FRINGE BENEFITS**:			$ 2,845
	26.3% of Direct Salaries & Wages (less students)			
III.	MATERIALS, SUPPLIES, AND SERVICES:			$ 1,300
	A.	Gases and Liquids for Experiments	$ 800	
	B.	Miscellaneous Project Supplies and Components	$ 500	
IV.	TRAVEL			$ 3,400
	A.	Travel for Students (2) to 1991 to AAS/ DPS Meeting (Palo Alto, CA, 2 students, 5 days duration each: air fare: $500 each, plus 5 days @ $80/day per student)	$ 1,800	
	B.	Travel to Hawaii for 2 observers at Mauna Kea (CSO) (Airfare only, $700 each)	$ 1,400	
		SUBTOTAL - ESTIMATE OF DIRECT COSTS		$43,363
V.	OVERHEAD (Indirect Expense)**: 62.5% of Modified Total Direct Cost Base			$27,102
		TOTAL ESTIMATED COST:		$70,465

*The salary and wage rates are based on projected FY 91 salaries for the Georgia Institute of Technology. The Georgia Tech Fiscal Year is July 1 through June 30.

**Rates are effective for the period July 1, 1989 through June 30, 1990 and are subject to adjustment thereafter upon DCAA audit and ONR negotiations.

IX. COGNIZANT PERSONNEL

For scientific or technical matters relating to the contract:

Paul G. Steffes
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0250
Telephone: (404) 894-3128

For contractual and business matters:

R. Dennis Farmer
Georgia Tech Research Corporation
Centennial Research Building
Georgia Institute of Technology
Atlanta, GA 30332-0250
Telephone: (404) 894-4814

X. BIOGRAPHICAL SKETCH

PAUL G. STEFFES
ASSOCIATE PROFESSOR
SCHOOL OF ELECTRICAL ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332-0250

EDUCATION

S.B.	Electrical Engineering	1977
S.M.	Electrical Engineering Massachusetts Institute of Technology	1977
Ph.D.	Electrical Engineering Stanford University	1982

EXPERIENCE

Massachusetts Institute of Technology, Research Laboratory of Electronics, Radio Astronomy and Remote Sensing Group Graduate Research Assistant	1976-1977
Watkins-Johnson Company, Sensor Development, San Jose, California Member of the Technical Staff	1977-1982
Stanford University, Electronics Laboratory, Center for Radar Astronomy, Stanford, California Graduate Research Assistant	1979-1982
Georgia Institute of Technology, School of Electrical Engineering, Atlanta, Georgia Assistant Professor Associate Professor	 1982-1987 1987-Present

EXPERIENCE SUMMARY

At Massachusetts Institute of Technology

Responsible for development, operation, and data analysis for an 8-channel, 118 GHz radiometer system flown aboard the NASA Flying Laboratory (CV-990) as an engineering model for a meteorological sensing satellite. Duties included hardware development of millimeter-wave, microwave, analog, and A to D segments of the system, in addition to airborne operation and reduction of data. The research resulted in a Master's thesis entitled "Atmospheric

Absorption at 118 GHz," detailing the first airborne measurement of high altitude atmospheric absorption in the 2.5 millimeter wavelength range, due to atmospheric oxygen.

At Watkins-Johnson Company

Responsibilities included customer proposals and system design and development, particularly in the area of millimeter-wave systems. Responsibility for millimeter-wave systems development included government sponsored study and development of ELINT (Electronic Intelligence) and radar warning receiving systems to frequencies as high as 110 GHz, as well as internal company sponsored development projects including a 60 GHz communications system and millimeter-wave downconverters.

At Stanford University

Research was concentrated in the area of microwave radio occultation experiments from Voyager and Mariner spacecraft, with specific interest in microwave absorption in planetary atmospheres. Work included computer-based theoretical development of microwave absorption coefficients for planetary atmospheres, to facilitate the use of radio occultation-derived microwave absorption profiles in determining constituent densities. Additional work included the development of a fully instrumented experimental facility for use in measuring the microwave properties of planetary atmospheres under simulated planetary conditions. The research resulted in a Ph.D. dissertation entitled "Abundances of Cloud-Related Gases in the Venus Atmosphere as Inferred from Observed Radio Opacity."

At Georgia Tech

Research Activities: Principal Investigator of the National Science Foundation Grant, "Remote Sensing of Clouds Bearing Acid Rain." This research studied and designed a microwave/millimeter-wave system for remotely sensing the pH of acidic clouds (1982-1983). Principal Investigator of the NASA Planetary Atmospheres Program, "Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres." This research includes study of the interaction between a number of atmospheric constituents and electromagnetic waves, along with applications of these studies to spacecraft and radio telescopic measurements of the microwave absorption in atmospheres of Venus and the outer planets (1984-1990). Principal Investigator of the GTE Spacenet Program, "Satellite Interference Locating System (SILS)." The program involves location of uplink signals on the surface of the earth without disrupting regular satellite operations (1986-1990). Principal Investigator of the Emory University/Georgia Tech Biomedical Technology Research Center, "Research in Development of a Non-Invasive Blood Glucose Monitoring Technique." This research involves the use of active infrared systems to determine glucose levels in the human eye and bloodstream (1988-1989). Principal Investigator of the NASA Pioneer Venus Guest Investigator Program, "Pioneer Venus Radio Occultation (ORO) Data Reduction: Profiles of 13 cm Absorptivity." This research infers 13 cm wavelength absorptivity profiles using the Pioneer Venus Orbiter, and then uses such profiles to characterize abundance profiles for gaseous H_2SO_4 in the Venus atmosphere (1988-1990). Director of the Ku Band Satellite Earth Station System. Responsible for development of a Ku-band uplink/

downlink system for use in inter-university networks. Co-investigator with Georgia Tech Research Institute (GTRI) of "Radar Warning Receiver Evaluations."

Teaching Activities: Resource Professor for "Satellite Communications Systems" (graduate course) and "Electromagnetics III" (undergraduate required course covering waves, waveguides, and antennas). Have also taught "Electromagnetics II" (electrodynamics), "Signals and Systems," and "Survey of Remote Sensing."

HONORS AND AWARDS

1. Member, Eta Kappa Nu.
2. Member, Sigma Xi.
3. Elected Senior Member, IEEE.
4. Recipient of the Stewart Award (MIT) for exceptional contribution to student extra-curricular life, 1977.
5. Recipient of the Metro Atlanta Young Engineer of the Year Award, presented by the Society of Professional Engineers, 1985.
6. Recipient of the Sigma Xi Young Faculty Research Award, 1988.
7. Appointed Member of the NASA Management and Operations Working Group for the Planetary Atmospheres Program (1986-1990).

PROFESSIONAL AFFILIATIONS

1. Member, American Association for the Advancement of Science.
2. Member, American Astronomical Society, Division for Planetary Sciences.
3. Member, American Geophysical Union.
4. Member, American Institute of Physics.
5. Member, American Society for Engineering Education.
6. Chairman, Atlanta Chapter, IEEE Antennas and Propagation Society and Microwave Theory and Techniques Society, 1986-1988.
7. Director, IEEE Atlanta Section, 1988-1989.

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2. P. G. Steffes, "Atmospheric Absorption at 118 GHz," S.M. Thesis, Massachusetts Institute of Technology, 1977.

3. P. G. Steffes, "Abundances of Cloud-Related Gases in the Venus Atmosphere as Inferred from Observed Radio Opacity," Ph.D. Dissertation, Stanford University, 1982.

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1. P. G. Steffes and R. A. Meck, "Prototype Tests Secure Millimeter Communications," *Microwave Systems News*, vol. 10, pp. 59-68, October 1980.

2. V. R. Eshleman, D. O. Muhleman, P. D. Nicholson, and P. G. Steffes, "Comment on Absorbing Regions in the Atmosphere of Venus as Measured by Radio Occultation," *Icarus*, vol. 44, pp. 793-803, December 1980.

3. P. G. Steffes and V. R. Eshleman, "Sulfur Dioxide and Other Cloud-Related Gases as the Source of the Microwave Opacity of the Middle Atmosphere of Venus," *Icarus*, vol. 46, pp. 127-131, April 1981.

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5. P. G. Steffes and V. R. Eshleman, "Sulfuric Acid Vapor and Other Cloud-Related Gases in the Venus Atmosphere: Abundances Inferred from Observed Radio Opacity," *Icarus*, vol. 51, pp. 322-333, August 1982.

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8. P. G. Steffes, "Evaluation of the Microwave Spectrum of Venus in the 1.2 to 22 cm Wavelength Range Based on Laboratory Measurements of Constituent Gas Opacities," *Astrophysical Journal*, vol. 310, pp. 482-489, November 1, 1986.

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13. P. G. Steffes, M. J. Klein, and J. M. Jenkins, "Observation of the Microwave Emission of Venus from 1.3 to 3.6 cm," *Icarus*, vol. 84, pp. 83-92, March 1990.

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2. P. G. Steffes and V. R. Eshleman, "Laboratory Measurements of the Microwave Opacity of Cloud Related Gases Under Simulated Conditions for the Venus Atmosphere, *Bulletin of the American Astronomical Society*, vol. 13, pg. 716, 1981.

3. P. G. Steffes and V. R. Eshleman, "Abundances of Cloud-Related Gases in the Venus Atmosphere: Implications from Observed Radio Opacity," *Proceedings of the International Conference on the Venus Environment*, Palo Alto, California, vol. 1, pg. 20, November 1981.

4. P. G. Steffes and V. R. Eshleman, "Sulfuric Acid Vapor and Other Cloud-Related Gases in the Venus Atmosphere: Abundances Inferred from Observed Radio Opacity," *Abstracts of the Fourth Annual Meeting of Planetary Atmospheres Principal Investigators*, University of Michigan, vol. 1, pp. 20-21, April 21-23, 1982.

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6. P. G. Steffes, "A Millimeter-Wave System for the Remote Sensing of Acidic Clouds and Precursor Gases in the Troposphere," *Digest of the Eighth International Conference on Infrared and Millimeter Waves*, Miami Beach, Florida, vol. 1, pp. 264-265, December 16, 1983.

7. P. G. Steffes, P. S. Stellitano, and R. C. Lott, "Measurements of the Microwave Opacity and Vapor Pressure of Gaseous Sulfuric Acid Under Simulated Venus Conditions," *Bulletin of the American Astronomical Society*, vol. 16, pg. 694, 1984.
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10. P. G. Steffes and D. H. Watson, "Constraints on Constituent Abundances in the Venus Atmosphere from the Microwave Emission Spectrum in the 1 to 20 cm Wavelength Range," *Bulletin of the American Astronomical Society*, vol. 17, pg. 720, 1985.
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Presented at the *21st Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society*, Providence, Rhode Island, October 31, 1989.

21. A. K. Fahd and P. G. Steffes, "Laboratory Measurements of the Dissociation Factor of Gaseous Sulfuric Acid (H_2SO_4)," *Bulletin of the American Astronomical Society*, vol. 21, pg. 927, 1989.
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22. J. Joiner and P. G. Steffes, "Models of the Millimeter-Wave Emission of the Jovian Atmosphere Utilizing Laboratory Measurements of Gaseous Ammonia (NH_3)," *Bulletin of the American Astronomical Society*, vol. 21, pg. 945, 1989.
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MARCH 1990

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REPORT

TO THE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

<u>**SEMIANNUAL STATUS REPORT #15**</u>

for

GRANT NAGW-533

LABORATORY EVALUATION AND APPLICATION OF

MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED

CONDITIONS FOR PLANETARY ATMOSPHERES

Paul G. Steffes, Principal Investigator

November 1, 1990 through April 30, 1991

Submitted by

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Georgia Institute of Technology
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TABLE OF CONTENTS

I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing atmospheric constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or using laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. For example, laboratory measurements performed by Joiner et al. (1989), under Grant NAGW-533, have shown that the millimeter-wave capacity of ammonia between 7.5 mm and 9.3 mm and also at the 3.2 mm wavelength is best described by a different lineshape than was previously used in theoretical predictions. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements and to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

One key activity in the first half of this grant year has continued to be laboratory measurements of the microwave and millimeter-wave properties of the simulated atmospheres of the outer planets and their satellites. However, we have also focussed on development of a radiative transfer model of the Jovian atmosphere at wavelengths from 1 mm to 10 cm. This model utilizes our laboratory data and has also been used to evaluate the need for laboratory measurements of other possible absorbers. This modeling effort has led us to conduct a laboratory measurement of the millimeter-wave opacity of hydrogen sulfide (H_2S) under simulated Jovian conditions. Since our modeling effort suggested that it was possible to determine limits on the abundance of H_2S in the atmosphere of Jupiter using a medium resolution observation at 1.4 mm, an observation of Jupiter was conducted in November, 1990, from the Caltech Submillimeter Observatory (CSO) in Hawaii. Descriptions of the modeling effort, the laboratory experiment, and the observation is given in Section II, and in Appendix B which is a preprint of a paper entitled "Modeling of the Millemeter-Wave Emission of Jupiter Utilizing Laboratory Measurements of Ammonia (NH_3) Opacity" by Joiner and Steffes, which has been submitted to the Journal of Geophysical Research: Planets.

An important source of information regarding the Venus atmosphere is the increasing number of high-resolution millimeter-wavelength emission measurements which have been recently conducted. (See, for example, de Pater et al., 1991) Correlative studies of these measurements with Pioneer-Venus radio occultation measurements (Jenkins and Steffes, 1991) and our longer wavelength emission measurements (Steffes et al., 1990) have provided new ways for characterizing temporal and spatial variations in the abundance of both gaseous H_2SO_4 and SO_2, and for modeling their roles in the subcloud atmosphere. However, unambiguous results require that we have dependable knowledge of the microwave and millimeter-wave opacity of gaseous <u>and</u> liquid H_2SO_4, and of gaseous SO_2 under Venus conditions.

While some laboratory measurements of the microwave absorption properties of gaseous SO_2 under simulated Venus conditions were made at 13 cm and 3.6 cm wavelengths by Steffes and Eshleman (1981), no measurements have been made at shorter wavelengths. Since the 1.35 cm wavelength appeared to be one of the better wavelengths for measuring the sub-cloud SO_2 abundance (Steffes <u>et al</u>., 1990), we have conducted laboratory measurements of the 1.35 cm (and 13 cm) opacity of gaseous SO_2. The results and application of this work were discussed in the previous <u>Annual Report (includes Seminannual Status Report #14)</u> for Grant NAGW-533 (11/1/89 - 10/31/90). However, during the first half of this grant year we have also conducted laboratory measurements of the absorptivity of gaseous SO_2 at the 3.2 mm wavelength under simulated Venus conditions. These measurements are described in Section III of this report.

Likewise, we have recently completed laboratory measurements of the millimeter-wave dielectric properties of liquid H_2SO_4, in order to model the effects of the opacity of the clouds of Venus on the millimeter-wave emission spectrum. This laboratory experiment and its results are described in Appendix C which is a preprint of a paper entitled "Laboratory Measurement of the Millimeter-Wave Properties of Liquid Sulfuric Acid (H_2SO_4)" by Fahd and Steffes, which has been submitted to the <u>Journal of Geophysical Research: Planets</u>.

In the second half of this grant year we intend to complete the analysis of our observations of the 1.4 mm emission spectrum of Jupiter. By using the results of our laboratory measurements of the 1.4 mm opacity of gaseous H_2S, combined with our radiative transfer model already developed for Jupiter, we hope to establish limits on the abundance and distribution of gaseous H_2S in the Jovian atmosphere. We will also begin construction of the laboratory apparatus for measurement of the millimeter-wave opacity from gaseous H_2SO_4 under simulated Venus conditions. This is an especially difficult task given the high temperatures required to obtain enough H_2SO_4 vapor so as to be able to measure its opacity, and the high pressures characteristic of the Venus atmosphere.

Finally, we intend to pursue an integrated multi-spectral analysis of Venus atmospheric data employing: 1) recent Pioneer-Venus radio occultation data for 13 cm opacity in the Venus atmosphere (ref. Jenkins and Steffes, 1991); 2) recent earth-based observations of the microwave (ref. Steffes et al., 1990) and millimeter-wave (ref. de Pater et al., 1991) emission from Venus, and 3) recent earth-based and spaced-based observations of the I.R. emission from Venus. Our study will also establish requirements for additional laboratory measurements, especially in the I.R. We are also studying the possibility of directly monitoring the signals from the Galileo Jupiter Probe with an earth-based radio telescope so that we could obtain another independent measurement of radio opacity at a localized position within the Jovian atmosphere.

II. OUTER PLANETS STUDIES

1 Measurement of (H_2S) Opacity at G-Band

1.1 Laboratory Configuration

A block diagram of the system used to measure H_2S absorption is shown in Figure 1. The G-Band CW signal (~218 GHz) is generated by doubling a W-Band (~109 GHz) klystron tube source. The klystron power supply provides modulation by varying the voltage on the reflector of the klystron. The variation in frequency using this technique is less than 0.5%. Since the pressure-broadened H_2S line is several GHz wide, absolute frequency stability is not necessary. A sample of the signal from the klystron is taken by a 20 dB coupler and downconverted to an IF of about 800 MHz by a harmonic mixer. A microwave source phase locked to a microwave frequency counter provides the LO for the mixer. The frequency and stability of the IF signal is monitored with a high resolution spectrum analyzer. The frequency of the klystron can be calculated from the precise measurement of the IF and LO frequencies using the spectrum analyzer and frequency counter.

High gain horn antennas are used to transmit and receive the G- band signal which passes through a 71 cm glass cell. A G-Band detector converts the received millimeter-wave signal to a voltage which is measured with a lock in amplifier. A 5 cm piece of WR-5 waveguide (f_c = 168 GHz) acts as a high pass filter to prevent any leakage of the fundamental or first harmonic (~ 109 GHz) through the doubler from being detected. A highpass filter (f_c = 300 GHz) was used to measure the signal level of the third harmonic (~ 327 GHz). The power from the third harmonic was found to be more than 30 dB down from the second harmonic. Thus, the detector is measuring power from only the desired harmonic.

Reflections occur at the cell boundaries due to the different dielectric constants of the air outside the cell, gas mixture in the cell, and lens material at the cell boundary. In order to measure the absorption due to the H_2S gas mixure, the power or voltage on the detector is first measured with the H_2S mixture in the cell. The power is then measured in the cell filled with a gas mixture of 90% hydrogen and 10% helium. This mixture has a similar index of refraction as that of the H_2S gas mixture. Thus, the reflections occurring at the cell boundaries will be similar for both gas mixtures. The absorption due to the hydrogen and helium mixure is negligible. The attenuation due to the H_2S mixure can be inferred from the ratio of the voltages measured with the two gas mixtures in the cell. This approach ensures that the drop in signal level is due only to absorption and not changes in reflection at the cell interfaces.

A pre-mixed, constituent analyzed gas mixture (Matheson) is used in all experiments. This mixture consists of 78.79% H_2, 9.28% He and 11.93% H_2S. A relatively high mixing ratio of H_2S is needed in order to measure absorption in the cell. The uncertainty in this mixture is $\pm 2\%$ of the stated component mixing ratio. The experiments take place at ambient temperature (296K) and at a total pressure of 2 atm.

The main source of uncertainty in this experiment is due to power drift in the klystron source. Power and frequency drift occur as the temperature of the klystron varies. Although the klystron is mounted on a large heat sink to reduce power and frequency drift, the output power exhibits a sinusoidal drift. By carefully characterizing the sinusoidal drift in power, the error bars have been minimized.

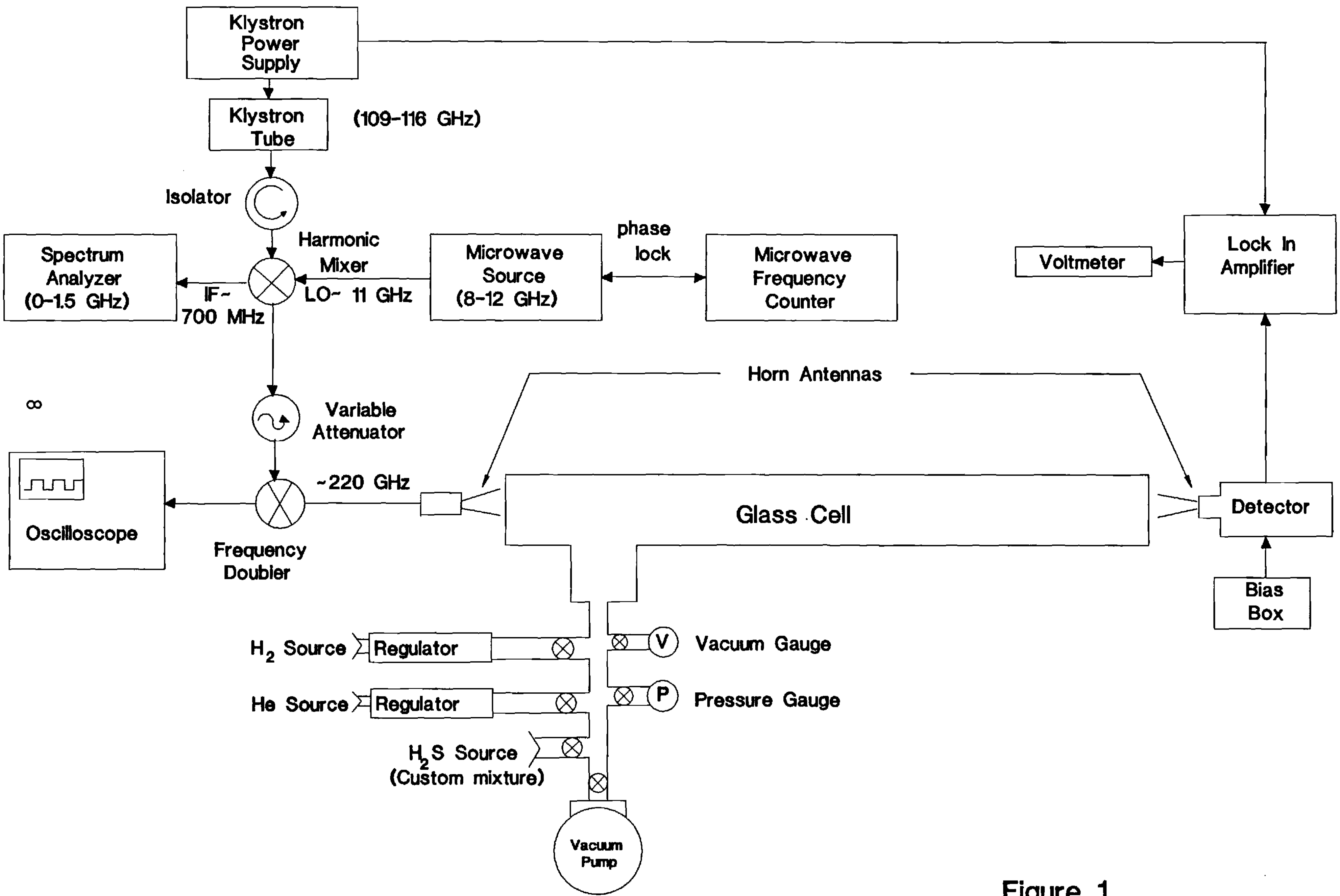
1.2 Experimetal Results

The pressure-broadened linewidth of H_2S in an H_2/He atmosphere can be expressed by

$$\Delta\nu = \left(\frac{T}{T_o}\right)^n \cdot \left[\Delta\nu_{H_2}P_{H_2} + \Delta\nu_{He}P_{He} + \Delta\nu_{H_2S}P_{H_2S}\right] \tag{1}$$

where $\Delta\nu_{HH}$ is the hydrogen-broadened linewidth and n is assumed to be 2/3. The self-broadened linewidths of several H_2S lines, including the $2_{0,2} - 2_{1,1}$ line at 217 GHz, have been measured by Helminger and De Lucia (1977). The reported value of the self-broadened line width of the $2_{0,2} - 2_{1,1}$ line, $\Delta\nu_{H_2S}$, is 9.10 MHz/Torr (6.92 GHz/bar). The helium-broadened linewidth, $\Delta\nu_{He}$ has been measured for the $1_{0,1} - 1_{1,1}$ line of H_2S at 168.8 GHz and at 295K by Wiley *et al.* (1989) and found to be 1.60 MHz/Torr (1.22 GHz/Bar). We assume the same value for the $2_{0,2} - 2_{1,1}$ transition.

The measured absorption at a pressure of 2 atm at room temperature is shown in Figure 2. The solid lines represent the theoretically computed absorption. The line parameters used in the absorption computation are taken from the GEISA line catalog. We use the Van-Vleck Weisskopf lineshape with the line width as given in Equation 1. The absorption in dB/m is calculated for several values of $\Delta\nu_{H_2}$. Visual inspection of Figure 1 reveals that the value of $\Delta\nu_{H_2}$ is approximately 2 ± 0.5 GHz/Bar (2.6 ± 0.7 MHz/Torr).



Klystron Power Supply
Klystron Tube
(109-116 GHz)
Isolator
Harmonic Mixer
Spectrum Analyzer (0-1.5 GHz)
IF~ 700 MHz
LO~ 11 GHz
Microwave Source (8-12 GHz)
phase lock
Microwave Frequency Counter
Voltmeter
Lock In Amplifier
Horn Antennas
Variable Attenuator
~220 GHz
Oscilloscope
Frequency Doubler
Glass Cell
Detector
Bias Box
H_2 Source
Regulator
He Source
Regulator
H_2S Source (Custom mixture)
Vacuum Gauge
Pressure Gauge
Vacuum Pump

Figure 1

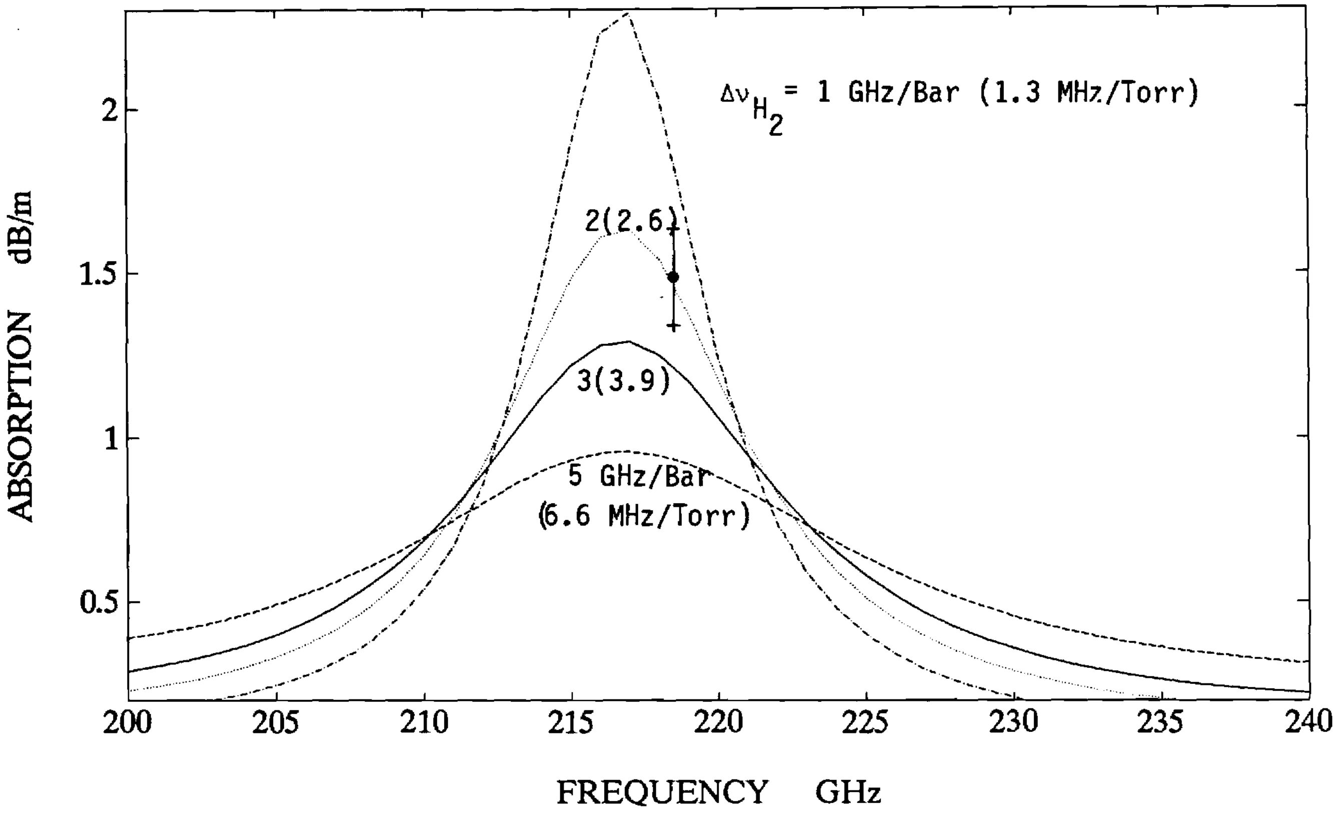


Figure 2: Result from laboratory measurement of the 1.4 mm opacity from H_2S in a H_2/He atmosphere. Note that the results are most consistent with a broadening parameter of 2 GHz/Bar , or 2.6 MHz/Torr.

2. Dual Wavelength Observation of Jupiter at 1.4 mm

2.1 Instrumentation

The observations were made with the 10.4m Caltech Submillimeter Observatory (CSO). The receiver is double side band with a band separation of 2.8 GHz. The receiver (double side band) temperatures measured at 215 and 230 GHz were 220K and 240K respectively. The Acousto-Optic Spectromoeter (AOS) has a total bandwidth of 500 MHz and 1024 channels.

We observed both Jupiter and Mars on November 25, 1990, with the LO centered at 215.3 GHz. The frequency of the $2_{0,2}$ - $2_{1,1}$ transition of H_2S (216.7 GHz) is then centered in the upper sideband. The two planets were observed on November 26, 1990, at a frequency 229.6 GHz. This frequency was chosen so that the CO transition at 230.5 GHz, which has been observed in the spectrum of Mars, would be in between the upper and lower sidebands. Therefore, it would not interfere with the observed continuum level of Mars.

Chopping was accomplished in the position switching mode. In this mode, the antenna is alternately pointed ON the source (planet) and at a position in the sky OFF the source 5' in either the + or - azimuth direction. The telescope remains ON the source and OFF the source for a duration of 10 seconds. One scan of the source is defined as 4 ON/OFF cycles resulting in a total integration time of 80 seconds per scan. A chopper wheel calibration is performed before each scan of the planet. This calibration removes the effects of the earth's atmospheric opacity.

Accurate pointing of the antenna is accomplished by constructing a five point map of the planet in order to calculate the center of the source. After initially centering the telescope on the planet, the pointing was accurate to better than 4". The telescope was typically repointed after every other scan.

2.2 Calibration

Brightness temperatures of 211.9 and 212.6K are assumed for Mars at 216 and 230 GHz, respectively. These temperatures are based on the models of Rudy (private communication, 1991). The calculated millimeter-wave emission from Mars is assumed to be accurate to within $\pm$ 10%.

The temperatures of the planets are corrected for partial filling of the antenna beam using the correction factor in Ulich *et. al.*, (1980). For Jupiter, we use an equatorial radius at the 1 bar level of 71495 km and an ellipticity of 0.065. This value is based on the radio occultation experiment aboard Voyager (Lindal *et al*., 1986). A value of 3397 km was assumed for the Mars equatorial radius with an ellipticity of 0.0006. These are the same values as those used by Griffin *et al*. (1986).

Ideally, the observations of Jupiter should be made when the calibrator (Mars) is close to the source (Jupiter) in the sky. In this case, the effects of any time or spatial variation in the earth's atmospheric opacity will be limited. However, good observations of Jupiter relative to Mars can still be made if the atmospheric opacity is relatively stable and both planets are observed at similar elevations.

2.3 Results

Analysis of this data is currently ongoing and should be completed by the end of this grant year.

III. VENUS STUDIES

Laboratory measurements of the opacity of gaseous SO_2 under Venus-like conditions:

Gaseous sulfur dioxide has long been recognized as one of the dominant absorbers present in the middle atmosphere of Venus (Steffes et. al, 1990). To fully understand the role of gaseous SO_2 on the observed millimeter-wave emission from Venus, a knowledge of the absorption of gaseous SO_2 in a CO2 atmosphere at millimeter-wave is necessary. This need has motivated a direct measurement of the opacity of gaseous SO_2 at 3.2 mm.

The experimental approach used to measure the absorptivity of gaseous SO_2 in a CO_2 atmosphere is similar to that previously used by Joiner and Steffes (1991) in determining the millimeter-wave opacity of NH_3 under Jovian-like conditions. A block diagram of the experimental setup is shown in Figure (3). In this setup, a Fabry-Perot resonator shown in Figure (4) is employed to measure the opacity of SO_2 at 94 GHz. The absorptivity is measured by observing the effects of the test gas mixture on the quality factors (Q's) of the Fabry-Perot resonator. For relatively low-loss gas mixtures, the relation between the absorptivity of the gas mixture and its effect on the Q and the transmissivity (t) of a particular resonance is given by:

$$\alpha=\frac{\pi}{\lambda}\left(Q_{mg}^{-1}(1-t_g^{-1/2})-Q_{me}^{-1}(1-t_e^{-1/2})\right)$$

where α is the absorptivity of the gas mixture in Nepers/Km, note: an attenuation constant, or absorption coefficient or absorptivity of 1 Neper/Km =2 optical depths per Km = 8.686 dB/Km where the first notation is the natural form used in electrical engineering, the second is the prevalent form used in physics and astronomy, and the third is the common (logarithmic) form. Q_{mg} is the measured quality factor with the gas mixture present while Q_{me} is the measured quality factor of the empty resonator. In addition, t_g denotes the transmissivity through the cavity at resonance with the gas mixture loaded while t_e denotes the measured transmissivity without the gas mixture. By using the above expression to calculate the absorption of gaseous SO_2, one can minimize the effect of dielectric loading which may be present in the system.

The results of our measurements are shown in Figure (5). In this figure, the absorption (normalized to mixing ratio) of gaseous SO_2 at two distinct pressures are compared with the theoretically calculated values of the opacity of SO_2 in accordance with the Van-Vleck Weiskopf formalism. As a result, we can state that our measured opacity agrees with the predicted values from the VVW model. These results are extremely important since they show that the f^2 dependence of the opacity of SO_2 which was proposed by Jansen and Poynter (1981) and adopted by Steffes and Eshleman (1981) for frequencies below 100 GHz is not valid.

Currently, we are working on incorporating our measurements into a radiative transfer model in order to investigate the role of SO_2 on the millimeter-wave brightness temperature of Venus.

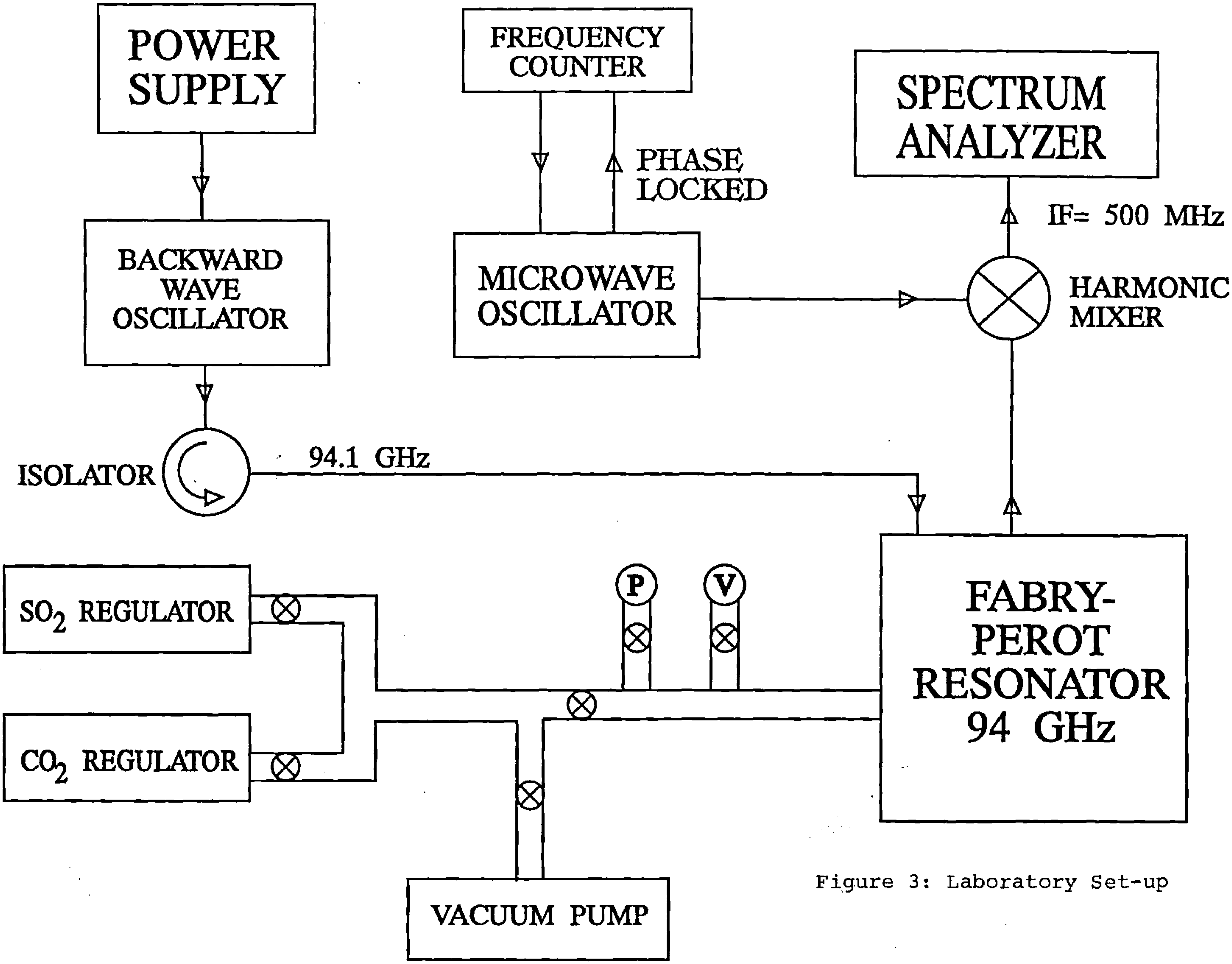


Figure 3: Laboratory Set-up

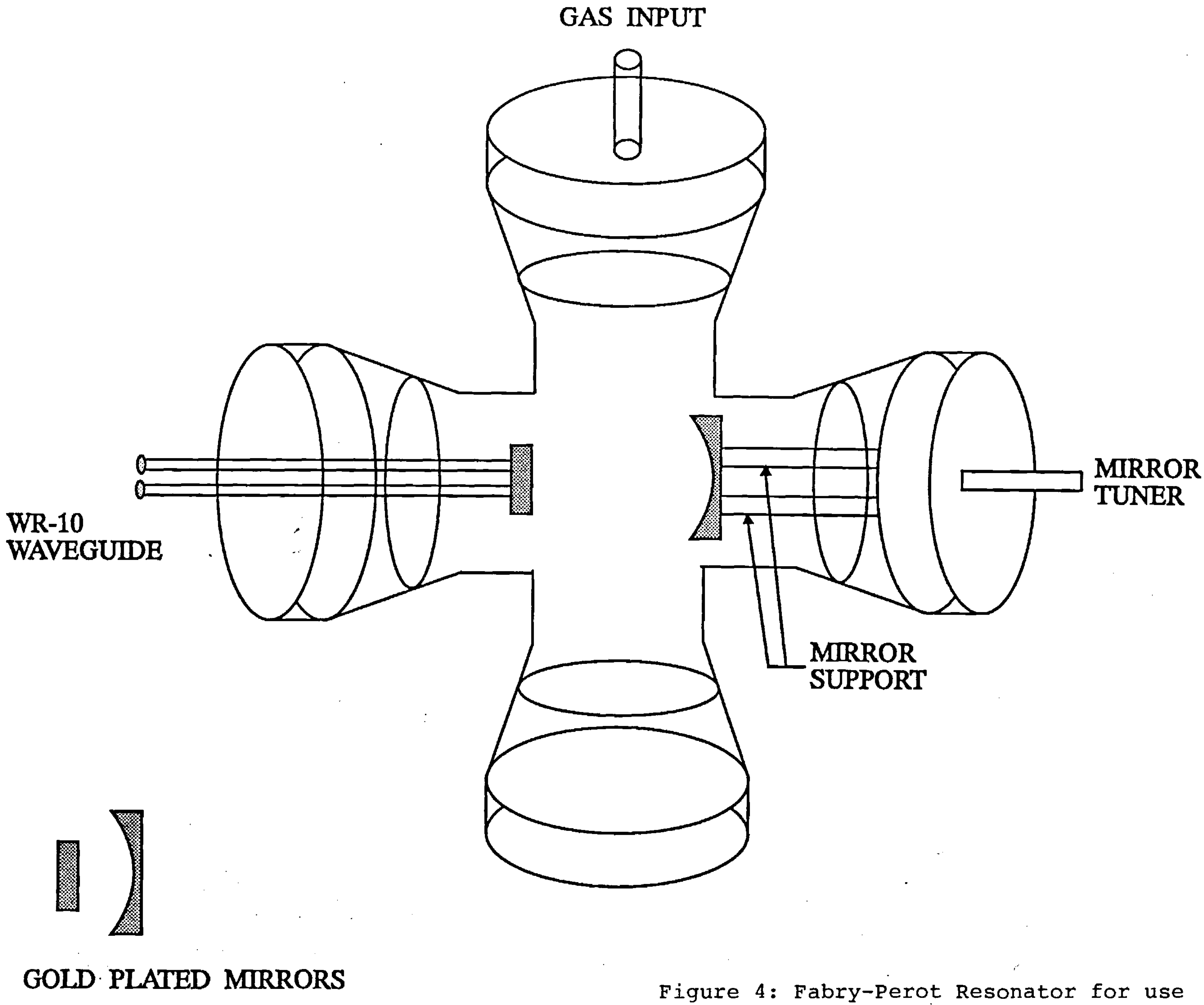


Figure 4: Fabry-Perot Resonator for use at 94 GHz.

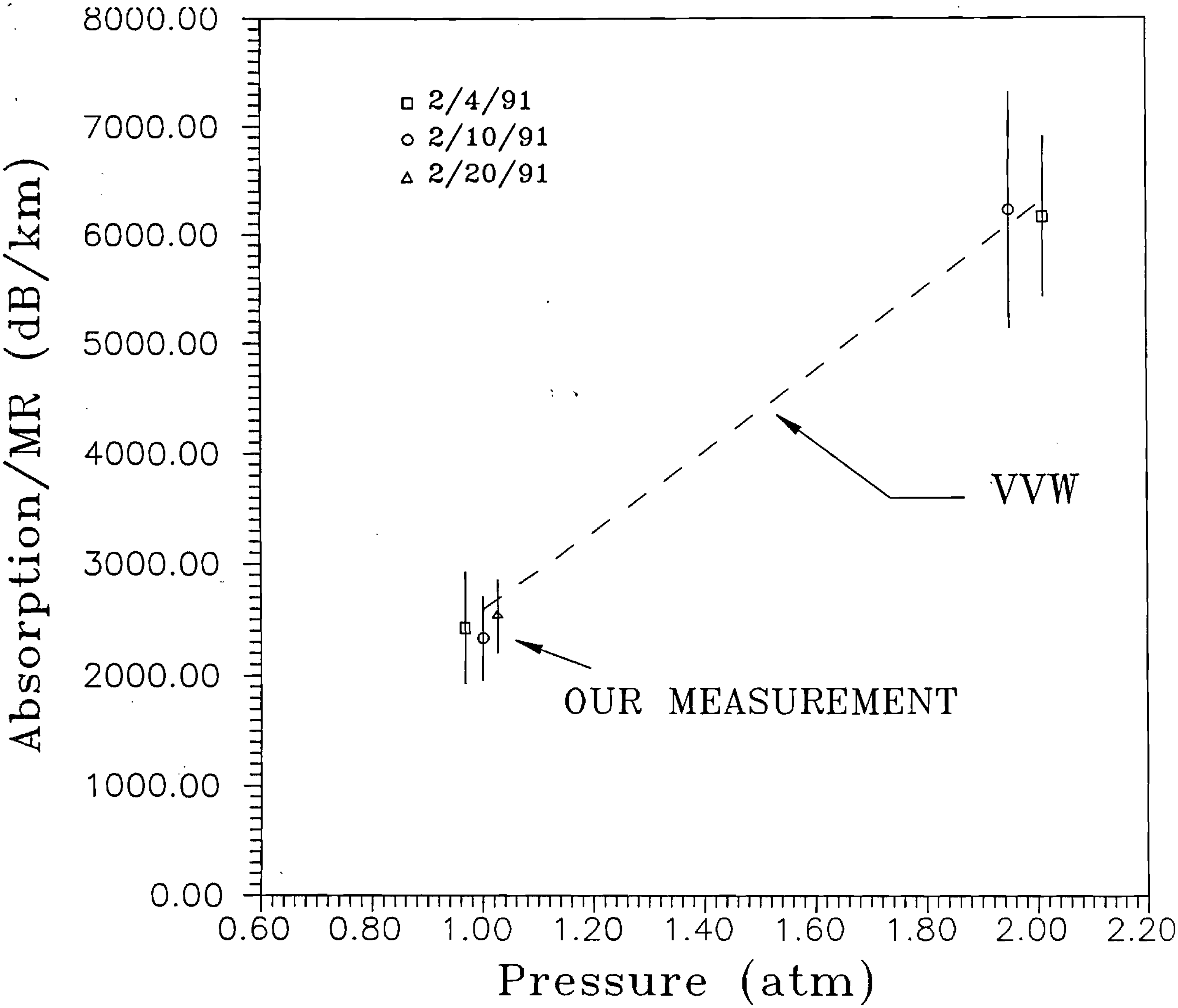


Figure 5: Results for the absorptivity (dB/km) of SO_2 in a CO_2 atmosphere. Note that the results are normalized by SO_2 mixing ratio. This experiment was conducted at a temperature of 293 K.

IV. PUBLICATIONS AND INTERACTION WITH OTHER INVESTIGATORS

After attending the October, 1990, AAS/DPS meeting (Charlottesville, VA) where we presented 4 papers (Fahd and Steffes, 1990a; Fahd and Steffes, 1990b; Joiner and Steffes, 1990; Jenkins and Steffes, 1990; see Appendix A), we prepared and submitted two papers to the new Journal of Geophysical Research: Planets. These papers are to be included in a special issue on Laboratory Research for Planetary Atmospheres. The first is entitled "Modeling of the Millimeter-Wave Emission of Jupiter Utilizing Laboratory Measurements of Ammonia (NH_3) Opacity" by Joiner and Steffes and is attached as Appendix B. The second is entitled "Laboratory Measurement of the Millimeter-Wave Properties of Liquid Sulfuric Acid (H_2SO_4)" by Fahd and Steffes and is attached as Appendix C.

Our work has been complemented by our past involvement in the Pioneer-Venus Guest Investigator Program in which we processed radio occultation data in order to obtain 13 cm absorptivity profiles for the Venus atmosphere (Jenkins and Steffes, 1991). This has kept us in close contact with a large number of Venus investigators. More informal contacts have been maintained with groups at the California Institute of Technology, with the Stanford Center for Radar Astronomy (Drs. V.R. Eshleman, G.L. Tyler, and T. Spilker, regarding Voyager results for the outer planets, and laboratory measurements), and with JPL (Drs. Robert Poynter, Samuel Gulkis, and Michael Klein, regarding radio astronomical observations of the outer planets and Venus). We have also worked with Dr. Imke de Pater (University of California-Berkeley) by using our laboratory measurements of atmospheric gases in the interpretation of radio astronomical observation of Venus and the outer planets. We have also studied possible effects of the microwave opacity of cloud layers in the outer planets' atmospheres. In this area, we have worked both with Dr. de Pater and with Dr. Paul Romani (Goddard SFC).

In the second half of this grant year, we will again submit results of our latest work to the annual AAS/DPS meeting. We will also submit a paper to the IEEE Transactions on Microwave Theory and Techniques describing our observations of Jupiter and accompanying laboratory measurements of H_2S at the 1.4 mm wavelength. (This will be submitted for a special issue on "Microwaves in Space" commemorating the International Space Year.) Finally, we will prepare and submit a paper to Icarus describing our laboratory measurements of the microwave and millimeter-wave opacity of SO_2, and how the results affect interpretation of the microwave and millimeter-wave emission from Venus.

V. CONCLUSION

In the first half of this grant year we have continued a very active program of laboratory measurements of the microwave and millimeter-wave properties of planetary atmospheric constituents. We have also been involved in observational and interpretive studies of the microwave and millimeter-wave emission from planetary atmospheres. In the second half we intend to complete the analysis of our observations of the 1.4 mm emission spectrum of Jupiter. By using the results of our laboratory measurements of the 1.4 mm opacity of gaseous H_2S, combined with our radiative transfer model already developed for Jupiter, we hope to establish strong limits on the abundance and distribution of gaseous H_2S in the Jovian atmosphere. We will also begin construction of the laboratory apparatus for measurement of the millimeter-wave opacity from gaseous H_2SO_4 under simulated Venus conditions. This is an especially difficult task given the high temperatures required to obtain enough H_2SO_4 vapor so as to be able to measure its opacity, and the high pressures characteristic of the Venus atmosphere.

Finally, we intend to pursue an integrated multi-spectral analysis of Venus atmospheric data employing: 1) recent Pioneer-Venus radio occultation data for 13 cm opacity in the Venus atmosphere (ref. Jenkins and Steffes, 1991); 2) recent earth-based observations of the microwave (ref. Steffes et al., 1990) and millimeter-wave (ref. de Pater et al., 1991) emission from Venus, and 3) recent earth-based and spaced-based observations of the I.R. emission from Venus. Our study will also establish requirements for additional laboratory measurements, especially in the I.R.

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VII. APPENDICES

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Laboratory measurement of the millimeter-wave properties of liquid sulfuric acid (H_2SO_4) between 90-100 GHz.

A.K. Fahd, P.G. Steffes (Georgia Institute of Technology)

Recent observations of the millimeter-wave emission from Venus at 115 GHz (2.6 mm) have shown significant variations in the continuum flux emission (de Pater et al., in press) which may be attributed to the variability in the abundances of the absorbing constituents in the middle atmosphere of Venus. Such constituents include gaseous H_2SO_4 and SO_2, and liquid H_2SO_4 (the cloud condensate). CO_2 is considered to be the major contributor to the millimeter-wave opacity but its abundance variability is low. Estimating the absorbing properties of any of these constituents at frequencies near 100 GHz is difficult since no laboratory measurements have been reported for Venus-like conditions. It has been proposed that the cloud condensate is the major source of this observed variability in the flux emission. This prediction assumed that the millimeter-wave opacity of liquid sulfuric acid is similar to that of water. However, since the microwave ($\lambda \geq 1$ cm) properties of water are substantially different from sulfuric acid (Cimino, 1982), a laboratory measurement of the complex dielectric constant of liquid H_2SO_4 at millimeter wavelengths is also needed.
Laboratory measurements of the dielectric properties of liquid sulfuric acid between 90-100 GHz have been conducted using a free space transmission setup to measure the complex dielectric constant of liquid sulfuric acid at room temperature for two acid concentrations (99% and 85% by weight). These results, plus a comparison between the opacity of liquid H_2SO_4 and water are presented.

* This work was supported by the Planetary Atmospheres Program of the National Aeronautics and Space Administration under grant NAGW-533.

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Appendix A 1

DIVISION FOR PLANETARY SCIENCES ABSTRACT FORM

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Laboratory measurements of the 1.3 and 13.3 cm. opacity of gaseous SO_2 under simulated conditions of the middle atmosphere of Venus.

A.K. Fahd, P.G. Steffes (Georgia Institute of Technology)

Gaseous sulfur dioxide has long been recognized as one of the dominant microwave absorbers in the middle atmosphere of Venus (Steffes, Icarus 1985,1990). This has motivated a direct measurement of the opacity of SO_2 at 1.3 and 13.3 cm wavelengths. Although some laboratory measurements of the microwave absorption properties of gaseous SO_2 under simulated Venus conditions were made at 13 and 3.6 cm. wavelengths by Steffes and Eshleman (Icarus, 1981), no measurements have been made at shorter wavelengths specifically at 1.38 cm.
The experimental approach used to measure the microwave absorptivity of gaseous SO_2 in a CO_2 atmosphere is similar to that used previously by Steffes (Icarus, 1985) for characterizing the absorption of gaseous H_2SO_4 in a CO_2 atmosphere. In short, the absorptivity is measured by observing the effects of the test gas mixture on the quality factors (Q's) of the microwave resonances between 2.2 and 22 GHz of two separate cavity resonators. The results at 2.24 GHz are consistent with results from Steffes and Eshleman (Icarus, 1981) in that the measured opacity is at least 50% larger than computed opacity from the Van Vleck-Weisskopf formalism. However, the 21.7 GHz (1.38 cm.) results are quite consistent with the Van Vleck-Weisskopf formalism. This result is extremely important since it shows that the f^2 dependence of SO_2 opacity which was proposed by Jansen and Poynter(Icarus, 1981) and adopted by steffes and Eshleman (Icarus, 1981) for frequencies below 100 Ghz and pressures greater than 1 Bar is not valid. As an application of our measurements, an estimate of the abundance of gaseous SO_2 is made possible by utilizing the Van Vleck-Weisskopf model of gaseous SO_2 along with the 1.35 cm. emission measured by Steffes et al. (Icarus, 1990).

* This work was supported by the Planetary Atmospheres Program of the National Aeronautics and Space Administration under grant NAGW-533.

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Appendix A 2

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Study of Millimeter-wave Absorbing Constituents in the Jovian Atmospheres

J. Joiner, P.G. Steffes (Georgia Institute of Technology)

The millimeter-wave absorption from gaseous ammonia (NH_3) has been previously measured under simulated Jovian conditions. When applied to models of the emission from Jupiter, the results suggested that some other absorber may be present at millimeter wavelengths. We have made measurements of the absorption from gaseous hydrogen sulfide (H_2S) under simulated Jovian conditions near the 1.4 mm rotational line in order to evaluate the pressure broadening effects of hydrogen and helium. We also give new expressions for the millimeter-wave pressure-induced absorption from hydrogen, helium, and methane, absorption from water vapor, potential absorption from cloud condensates and apply these expressions to models of the millimeter-wave emission from the Jovian planets.

*This work was supported by NASA Grant NAGW-533. This material is also based on work supported by NASA through the Georgia Tech Space Grant Consortium.

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Sulfuric Acid Vapor Profiles for the Atmosphere of Venus below the Main Cloud Deck

J.M. Jenkins, P.G. Steffes (Georgia Institute of Technology)

Observations of the 1.35 to 3.6 cm emission from Venus have suggested that significant temporal and/or spatial variations in the abundance and distribution of gaseous sulfuric acid below the main cloud layer (48 km and below) may be occurring. To investigate these phenomena, we have processed 13-cm Pioneer-Venus radio occultation data from 19 orbits in 1986 and 1987 to obtain 13-cm absorptivity profiles and sulfuric acid vapor abundance profiles. The data span a range of latitudes from 11°N to 88°N, solar zenith angles from 66° to 160° and probe altitudes as deep as 41 km (above a mean surface radius of 6051.3 km). Statistical uncertainties in the derived profiles have been characterized, allowing us to evaluate the statistical significance of spatial variations in the abundance and distribution of sulfuric acid vapor.

* This work was supported by NASA Grant NAG 2-515. This material is also based on work supported under a National Science Foundation Graduate Fellowship.

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Modeling of the Millimeter-wave Emission of Jupiter Utilizing Laboratory Measurements of Ammonia (NH_3) Opacity

JOANNA JOINER AND PAUL G. STEFFES

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Radiative transfer models which have been used to calculate the millimeter-wave emission from Jupiter do not agree well with the existing radio astronomical observations (*e.g.* dePater and Massie, 1985). This apparent discrepancy has gone largely unexplained due to a lack of laboratory data at these wavelengths coupled with uncertainties in the calibration of existing radio astronomical observations. Previous laboratory measurements of the 7.5 to 9.38 mm opacity from gaseous ammonia (NH_3) by Joiner *et al.* (1989) were inconclusive as to which theoretical lineshape most accuratedly describes the behavior of NH_3 at these wavelengths. We have made additional laboratory measurements of the millimeter-wave opacity of gaseous ammonia at a shorter wavelength (3.2 mm) where the theoretical lineshapes are further separated. The measurements were conducted at a temperature of 210K, at pressures ranging from 1 to 2 atm, and in a mixture consisting of 85.56% hydrogen (H_2), 9.37% helium (He), and 5.07% ammonia (NH_3). We have given a revised formalism for the Ben-Reuven lineshape in order to predict the absorption from NH_3 in an H_2/He atmosphere. We investigate several other potential candidates for millimeter-wave absorption and give revised formalisms for computing their absorption. We have compiled a list of reliable millimeter-wave radio astronomical observations of Jupiter. We compare our revised list of observations to calculated emission spectra which utilize revised expressions for the absorption from NH_3 as well as other opacity sources.

1. Introduction

The millimeter-wave spectrum is a one of the few regions capable of probing beneath the dense cloud layers of Jupiter. The measured emission from Jupiter at microwave frequencies (below 30 GHz) can be well explained by models using various profiles for the abundance of ammonia (NH_3), the dominant absorber at these frequencies. However, when the same models are used to calculate the emission at millimeter wavelengths, a discrepancy is found to exist between the calculated emission and the existing radio astronomical observations (see *e.g.* dePater and Massie, 1985). Because there are several sources of uncertainty in both the observations and the models, inferring information from millimeter-wave spectra of Jupiter is difficult.

One of the largest sources of uncertainty in modeling the millimeter-wave emission from the outer planets involves the calculation of the absorption coefficient of the atmospheric constituents. There are several sources of opacity in the millimeter-wave spectra of Jupiter. The dominant absorber at millimeter wavelengths is gaseous ammonia (NH_3). Another source of millimeter-wave opacity is pressure-induced absorption from hydrogen, helium, and methane. Bezard *et al.* (1983) first demonstrated that gaseous hydrogen sulfide (H_2S), which has yet to be detected on the outer planets, may be contributing to the opacity observed in Jupiter's millimeter-wave spectrum. Both H_2S and H_2O have strong rotational lines at millimeter wavelengths. Cloud particles may provide another source of millimeter-wave opacity. Although molecules such as PH_3, HCN, and CO contain strong absorption lines at millimeter wavelengths, they do not exist in abundances great enough to significantly affect the millimeter-wave spectrum of Jupiter.

Accurate calibration of the radio astronomical observations of the outer planets at millimeter wavelengths is critical if meaningful comparisons are to be made between different observations and between the observations and radiative transfer models. The most frequently used calibrator at these wavelengths is Mars. However, the uncertainty in the modelled flux from Mars is reported to be at least 10% (Griffin *et al.* , 1986) and could be as high as 20% (Orton, *private communication*, 1989). Before the millimeter-wave spectrum of Jupiter is fully understood, better calibration techniques will be needed. In addition, laboratory studies of potential absorbers are needed in order to interpret the measured emission from Jupiter correctly.

This paper describes the techniques used to make laboratory measurements of the millimeter-wave opacity from gaseous ammonia under simulated Jovian conditions. The results of these experiments are applied to radiative transfer models which are used to compute the millimeter-wave emission from Jupiter. Other sources of millimeter-wave opacity in the Jovian atmospheres are also examined. New expressions for the microwave and millimeter- wave absorption from NH_3, H_2O, cloud condensates, and pressure-induced absorption from H_2, He and CH_4 are given and applied to the radiative transfer model. Reliable millimeter-wave observations are then compared to calculated emission spectra utilizing expressions for the absorption from various atmospheric constituents based on recent laboratory studies.

2. Measurements of NH_3 Opacity at 3.2 mm

The absorption from gaseous ammonia (NH_3) in a simulated Jovian atmosphere has been measured at 7.5-9.38 mm (32-40 GHz) by Joiner *et al.* (1989). These measurements were compared to three theoretical formalisms. Although the data appeared to rule out the Van-Vleck Weisskopf (1945) lineshape, it was not clear whether the Gross (1955) lineshape or some modified form of the Ben-Reuven (1966) lineshape most accurately described the behavior of NH_3 at millimeter wavelengths. In order to further evaluate the millimeter-wave absorption from gaseous NH_3, we have made measurements of its opacity at a frequency of 94 GHz (3.2 mm) under simulated conditions for the Jovian planets. At this frequency the lineshapes differ by a significant amount, thus allowing a more accurate determination of the absorbing properties of ammonia at the high frequency tail of its pressure-broadened inversion spectrum. These experiments represent the first time that the opacity of gaseous NH_3 at wavelengths shortward of 7.5 mm has been measured under simulated conditions for the Jovian atmospheres.

Laboratory Configuration

The laboratory measurements are conducted using the W-Band millimeter-wave planetary atmospheres simulator shown in Figure 1. The W-Band millimeter-wave source consists of a power supply and backward wave oscillator (BWO) tube which act together as a millimeter-wave sweep oscillator. The millimeter-wave oscillator sweeps over the entire frequency range affected by the resonance in the Fabry-Perot resonator. The resonator is located inside a temperature chamber (ultra-low temperature freezer). Rigid pieces of WR-10 waveguide connect the resonator to the millimeter-wave source and receiver located outside the temperature chamber. The receiver utilizes a harmonic mixer in which the local oscillator (LO) is a microwave source which is phased locked to a microwave frequency counter. The frequency of the LO is approximately 9.25 GHz. The tenth harmonic of the LO is then mixed with the outgoing signal from the resonator producing an intermediate frequency (IF) of about 1.5 GHz. The IF signal is coupled from the mixer to the high resolution spectrum analyzer. The spectral response of the resonator is then viewed with the high resolution spectrum analyzer.

Fig. 1

The W-band Fabry-Perot resonator shown in Figure 2 consists of two gold plated mirrors, one flat and one spherical, which in effect produce a bandpass filter at the resonance. Electromagnetic energy is coupled both to and from the resonator through twin irises located on the flat mirror. The flat and curved mirrors have diameters of 5 and 11.5 cm respectively. The separation between the two mirrors is approximately 15 cm. This type of configuration yields superior focusing which is evident in the high quality factor (Q) of the resonator which is on the order of 25000.

Fig 2

The W-band resonator is contained in a cross shaped glass pipe with the curved mirror resting on two fixed support arms. The fixed arms can be adjusted in order to change the distance between the mirrors without disturbing the sensitive alignment of the mirrors. Each of the open ends of the pipe is sealed with an O-ring sandwiched between the glass lip and a flat brass or aluminum plate which is bolted to an inner flange. One of the plates contains an inlet for the gas to be introduced and evacuated. A network of 3/8" stainless steel tubing and valves connects the resonator to cylinders containing the various gases used in the experiments (H_2, He, and custom mixture). In addition, the pipes are also connected to an oil diffusion vacuum pump, a thermocouple vacuum gauge tube (0-27 Torr), and a positive pressure gauge (0-100 PSIG). Each component may be isolated from the system using the valve configuration shown in Figure 1. The system is capable of containing two atmospheres of pressure without detectable leakage. The experiment takes place indoors with the gases being released outdoors through a vent pipe where they are safely diluted by air. A flammable gas detector is used to detect any leaks that may occur during the experiment.

Experimental Approach

The absorption from gaseous ammonia can be calculated by observing changes in the bandwidth and center frequency of a resonance with and without the absorbing gas present. For a low- loss gas such as NH_3, if the percentage change in the center frequency of the resonance with and without the NH_3 present is small (for our experiment, the percentage change is approximately 0.3%), then the absorptivity can be expressed as

$$\alpha \simeq (BW_L - BW_O)\frac{2\pi}{c} = 2.096 \cdot 10^{-4}(\Delta BW) \quad cm^{-1} \quad (2.2)$$

where ΔBW is the change in bandwidth (in MHz) of the resonance with and without the absorbing gas present.

In order to evaluate Equation 2.2, the loaded bandwidth of the 94 GHz resonance, BW_L, is first measured while the gas chamber is filled with a premixed H_2/He/NH_3 mixture. The quantity BW_O is found by measuring the bandwidth in an H_2/He mixture (no NH_3 present) instead of using the bandwidth measured in an evacuated chamber. This approach accounts for the *dielectric loading* effect which is described at length in Joiner *et al.* (1989).

In order to observe the absorption due to ammonia with our system, a fairly high mixing ratio of NH_3 is needed. A premixed, constituent analysed mixture (Matheson) consisting of 85.56% H_2, 9.37% He, and 5.07% NH_3 is used in all experiments. In order to avoid condensation, the experiments take place at a temperature of 210 K. The pressures of the experiments range from 1 to 2 atm.

Experimental Uncertainties

The main contribution to the uncertainty in this type of measurement is due to noise in the system. This noise is visible when measuring the bandwidth of a resonance with the spectrum analyser. The uncertainty in measured absorptivity due to noise in our system is on the order of ± 20-25%. Other uncertainties are due to instrumental error and include the uncertainty in the ammonia mixing ratio, uncertainty in the measurement of total pressure, and variations in the chamber's temperature. The combined uncertainties in the absorption coefficient resulting from these three sources is approximately ±5%. The total uncertainty from all sources is reflected in the reported error bars.

The uncertainty in the measurement of center frequency and bandwidth (disregarding noise) is affected by the microwave LO source as well as the spectrum analyser. By phase locking the microwave LO source to a microwave frequency counter and properly calibrating the spectrum analyser, these uncertainties become negligible.

Experimental Results

Several different theories have been used to describe the frequency dependent part of the collision or pressure broadening of NH_3 inversion lines broadened in a H_2/He atmosphere. The Van Vleck-Weisskopf (1945) lineshape is known to be accurate at low pressures (less than 1 atm). Zhevakin and Naumov (1963) derived a different lineshape and found that their lineshape gave better results than the Van Vleck-Weisskopf theory when applied to experimental data regarding atmospheric water vapor absorption. This lineshape was also derived independently by Gross (1955). It is sometimes referred to as the kinetic lineshape. The formalisms for computing these lineshapes are given in Joiner *et al.* (1989). Ben-Reuven (1966) derived a more comprehensive lineshape which was found to be more accurate at higher pressures. This lineshape can be shown to reduce to the other lineshapes under certain conditions. The parameters of this lineshape may be varied in order to be compatible with laboratory measurements as in Berge and Gulkis (1976) and as we have done below. Figure 3 shows a graph of the calculated absorption from ammonia based upon four of the theoretical formalisms described above. The center frequencies and self-broadened linewidths (γ_o) of the NH_3 inversion resonances used in all calculations are taken from Poynter and Kakar (1975). The submillimeter lines are calculated as in dePater and Massie (1985) except that the Gross lineshape is used instead of the Van Vleck- Weisskopf lineshape.

The results of the measurements of NH_3 absorption at 3.2 mm are given in Table 1 along with the theoretically-derived values using various formalisms. It is clear that neither the Van Vleck-Weisskopf nor the Gross lineshapes provides a good fit to these measurements. We have modified the parameters of the Ben- Reuven lineshape in order to be compatible with the results of this work as well as the work of Morris and Parsons (1970), Steffes and Jenkins (1988), Joiner *et al.* (1989) and Spilker (1990). This formalism employs the Ben-Reuven lineshape as described in Berge and Gulkis (1976) with the pressure-broadened linewidth and coupling element given by Table1

$$\gamma(j,k) = 1.69P_{H_2}\Big(\frac{300}{T}\Big)^{2/3} + 0.75P_{He}\Big(\frac{300}{T}\Big)^{2/3} + 0.6P_{NH_3}\Big(\frac{300}{T}\Big)\gamma_o(j,k) \quad GHz \qquad (2.3)$$

$$\zeta(j,k) = 1.35P_{H_2}\Big(\frac{300}{T}\Big)^{2/3} + 0.3P_{He}\Big(\frac{300}{T}\Big)^{2/3} + 0.2P_{NH_3}\Big(\frac{300}{T}\Big)\gamma_o(j,k). \quad GHz \qquad (2.4)$$

No additional correction term is used in this formalism.

3. Application of Results to Radiative Transfer Model

A forward modeling approach is taken in which the parameters of the radiative transfer model are varied in an attempt to fit the calculated emission spectra to radio astronomical observations. The disk-average brightness of a planet, at a frequency ν is given by

$$B_\nu(T_D) = 2\int_0^1 \int_0^\infty B_\nu(T) exp\Big(-\frac{\tau}{\mu}\Big) d\tau\, d\mu. \qquad (3.1)$$

where $B_\nu(T)$ is the Planck function The quantity μ is the cosine of the senith angle. The senith angle at a given point on a constant pressure surface in the atmosphere of the planet is defined as the angle between the line of sight to the planet and the local normal to the surface at that point. The optical depth, τ, is defined as

$$\tau_\nu(z) = \int_0^z \alpha_\nu(z)dz \tag{3.2}$$

where z is the depth as measured from the top of the planet and $\alpha_\nu(z)$ is the sum of all the absorbing processes at a frequency ν. The pressure may be related to depth in the atmosphere by the hydrostatic equation and the equation of state.

The integral in Equation 3.1 is evaluated downward from the top of the atmosphere ($z = 0$) and is terminated when a value of 5 optical depths for τ is reached. We have evaluated the integral over μ in Equation 3.1 for Jupiter using two methods. The first method takes into account the oblate shape of the planet by using a grid approach (*e.g.* dePater and Massie, 1984). The second method assumes a spherical shape for the planet. Since the two methods differed by less than 1K or about 0.05%, we use the spherical approximation for all model calculations.

Temperature-Pressure Profile

The temperature-pressure profile, T(P), is calculated as in Briggs and Sackett (1989). A saturated adiabatic lapse rate is used as the calculation of T(P) evolves from deep in the atmosphere. The parameters for latent heat release are taken from Briggs and Sackett (1989). The *intermediate* case for the specific heat of hydrogen (Wallace, 1980) is assumed. The T(P) profile is calculated iteratively and constrained to meet the 1 bar temperature of 165K derived from the *Voyager* radio occultation experiments (Lindal *et al.*, 1981). At pressures from 10 mbar to 1 bar, a T(P) profile derived from *Voyager* data is used, which corresponds to the whole Jovian disk (similar to Besard *et al.*, 1983). The T(P) profile is shown in Figure 4.

Pressure-Induced Absorption

Pressure-induced absorption is caused by the transient dipole which is induced by intermolecular forces in colliding H_2-H_2, H_2-He, and H_2-CH_4 molecules. Goodman (1969) developed a simple expression for calculating the microwave and millimeter-wave pressure-induced absorption of H_2-H_2 and H_2-He pairs. We have updated this expression so that it is consistent with empirical expressions which have been used to describe more recent laboratory data taken at infrared wavelengths by Bachet *et al.* (1983) and Dore *et al.* (1983). New parameters for the temperature and pressure dependencies in the Goodman (1969) expression have been fit to a six parameter model from Borysow *et al.* (1985). A term which accounts for the H_2- CH_4 absorption has also been added. The parameters for this expression were optimised for temperatures and pressures corresponding to Jupiter's atmosphere. The new expression is

$$\alpha_{H_2} = \frac{3.56e-11}{\lambda^2} P_{H_2} \cdot \left[P_{H_2}\left(\frac{273}{T}\right)^{3.12} + 1.38 P_{He}\left(\frac{273}{T}\right)^{2.24} + 9.32 P_{CH_4}\left(\frac{273}{T}\right)^{3.34} \right] \; cm^{-1} \tag{3.3}$$

where P_{H_2}, P_{He}, P_{CH_4} are the partial pressures of hydrogen, helium, and methane in bars and λ is the wavelength in cm: This expression deviates from the Borysow formalism by less than 1% for temperatures and pressures at altitudes above the 10 bar level in Jupiter's atmosphere. For the Jovian conditions in the 10 to 100 bar region, the new expression deviates from the Borysow formalism by less than 10%.

H_2O Absorption

We use an expression for water vapor absorption under Jovian conditions which is based on laboratory data under terrestrial conditions. The parameters for the water vapor lines (*i.e.* transition frequencies, line strengths, linewidths) are summarized in Ulaby *et al.* (1981) from a more detailed compilation given in Waters (1976). This calculation includes ten rotational lines with frequencies up to 448 GHz. The kinetic lineshape is used in this calculation along with a correction term which was empirically derived by Gaut and Reifenstein (1971). The term P appearing in the expressions given by Ulaby *et al.* (1981), representing the pressure under terrestrial conditions, is replaced by $(0.81P_{H_2} + 0.25P_{He})$ in order to take into account the broadening characteristics of the Jovian atmosphere.

H_2S Absorption

Several strong rotational lines of H_2S appear in the millimeter spectrum at frequencies near 168, 217 and 300 GHz. We use a model of hydrogen sulfide absorption which is based on line strengths and center frequencies given in the GEISA catalog. We estimate the nitrogen-broadened line width to be approximately 2 GHz/bar based on its broadening of NH_3 and H_2O. We use a pressure-broadened linewidth of $d\nu = 2 \cdot (0.81P_{H_2} + 0.25P_{He})\left(\frac{300}{T}\right)^{2/3}$ GHz/bar and the Gross lineshape.

Cloud Absorption

An expression for the absorption due to cloud condensates based on Rayleigh scattering has been integrated into our radiative transfer model. In the Rayleigh regime, the absorption is expressed by

$$\alpha = \frac{18\pi M}{\rho\lambda} \cdot \left[\frac{\epsilon''}{(\epsilon'+2)^2 + \epsilon''^2}\right] \; cm^{-1} \tag{3.4}$$

(Battan, 1973) where ρ is the density of the condensation particle, M is the bulk density of the cloud in the same units, λ is the wavelength in cm, and $\hat{\epsilon} = \epsilon' - j\epsilon''$ is the complex dielectric constant of the cloud material (related to the complex index of refraction, $\hat{n} = n - jk$, by $\hat{\epsilon} = \hat{n}^2$).

Using Equation 3.4 along with models for cloud bulk densities based on equilibrium condensation models (see *e.g.* Briggs and Sackett, 1989), cloud opacity has been added to our Jovian model. The bulk densities calculated with equilibrium condensation models assume total condensation and thus the maximum expected bulk densities of cloud condensates. Romani (*private communication*, 1990) suggests that the actual cloud densities on Jupiter may be a factor of 5 lower than those predicted with equilibrium condensation models. Thus, the cloud bulk density will be taken as a variable in the calculating the absorption from cloud condensates.

Previous models have included only the contribution from the NH_3 ice cloud. However, weighting functions show that most of the emission from Jupiter at millimeter wavelengths originates from pressures levels between 1 and 3 bars. Thus, the potential contributions from any NH_4SH cloud as well as from H_2O (ice and aqueous solution) clouds should also be included. Because the complex index of refraction of the condensates at these wavelengths is not known, values were extrapolated from laboratory measurements in the infrared by Sill *et al.* (1980). A values of 1.3 is used for n_{NH_3}, the real part, and values between 0.01 and 0.05 for k_{NH_3}, the imaginary part of the index of refraction are used in our model program. Similarly, a value of 1.7 (CRC) is used for n_{NH_4SH} and values between 0.01 and 0.05 are used for k_{NH_4SH}. Values of 1.78 for n_{H_2O} and 0.01 for k_{H_2O} (ice) are taken from Ulaby *et al.* (1981). An expression for absorption by liquid water is given in Briggs and Sacket (1989).

4. Discussion

We have surveyed the existing microwave and millimeter-wave observations of Jupiter and compiled a list of reliable observations to use as a basis for comparison with theoretically computed spectra of Jupiter. A list of reliable observations published at frequencies from 36 to 300 GHz (1-8.35 mm) is given in Table 2 along with corresponding calibration sources and spectral bandwidths. Klein and Gulkis (1978) have normalized all of the observations between 14.5 and 36 GHz (8.35-20.7 mm) to a common flux scale. At longer wavelengths, Berge and Gulkis (1976) have given a survey in which the observations have been based on a common flux scale whenever possible.

Vertical distributions of NH_3, H_2S and H_2O have been derived by assuming various sub-cloud mixing ratios for cloud-forming constituents and using equilibrium condensation models. The derived abundance profiles are then used in the radiative transfer model in order to predict the emission from Jupiter. Four distributions for NH_3, two for H_2S and one for H_2O are shown in Figure 4. Abundance profiles for NH_3 assume deep mixing ratios of $2.5 \cdot 10^{-4}$ and $3.0 \cdot 10^{-4}$ which correspond to the measured value and upper limit derived by Bjoracker *et al.* (1986a) at $5\mu m$. Distributions for H_2S assume sub-cloud mixing ratios equal to the solar abundance ($3.55 \cdot 10^{-5}$) and nearly ten times the solar abundance ($2.2 \cdot 10^{-5}$) respectively. The H_2S is rapidly depleted due to a reaction with NH_3 to form NH_4SH. The H_2S distributions are compatible with the upper limits derived by Larson *et al.* (1984) at $2.7\mu m$. For sub-cloud H_2S mixing ratios less than or equal to the solar abundance, the NH_3 mixing ratio is not significantly depleted (as in NH_3 distributions 1a and 1b). However, if the H_2S mixing ratio is increased to $2.2 \cdot 10^{-5}$ (as in distribution 2), NH_3 becomes depleted near 2 bars (as in NH_3 distributions 2a and 2b). The formation of an NH_3 ice cloud further depletes the ammonia near 0.75 bar. The H_2O distribution assumes a sub-cloud mixing ratio equal to the solar abundance ($1.23 \cdot 10^{-3}$) and is depleted by the formation of an ice and aqueous H_2O cloud.

The distributions and cloud bulk densities shown in Figure 4 may not represent the actual distributions in Jupiter's atmosphere, but are used as a basis to test the effects of the various absorbers on the computed Jovian spectrum. For example, the actual H_2O distribution in Jupiter's atmosphere may be depleted by a factor of 100 (Bjoracker *et al.*, 1986b). The H_2O distributions and bulk densities shown in Figure 4 are used to illustrate the maximum possible effect of H_2O (gas and clouds) on Jupiter's emission. Although actual distribution of gases within the belts and zones of the planets will vary from the those shown in Figure 4, the distributions we show represent values averaged over the disk of the planet and hence are used to calculate disk-averaged brightness temperatures.

In Figure 5, the observed Jovian spectrum is shown along with calculated emission spectra. The model calculations include only NH_3 and H_2O opacity and use the four NH_3 distributions shown in Figure 4. The error bars for observations using Mars as the primary calibrator include a 10% uncertainty for the calibration in addition to the systematic uncertainties reported in Table 2. Model calculations using all four NH_3 distributions provide a good fit to observations near 1.3 cm and at longer wavelengths. However, only NH_3 distributions 1a and 1b provide a good fit to the millimeter-wave observations. The influence of the 183 GHz H_2O line on the computed emission is small for NH_3 distributions 1a and 1b.

The effect of adding H_2S opacity to model Jovian emission for two NH_3 distributions is shown in Figure 6 (solid line: NH_3 and H_2S opacity only, dashed line: NH_3, H_2O and H_2S opacity). In order to account for the large bandwidths of many of the observations, the contribution from the H_2S lines are averaged over 70 GHz. The average contribution (dotted line) from H_2S is small for NH_3 distribution 1b but substantial for NH_3 distribution 2a. Bezard *et al.* (1983) have shown the potential effects of H_2S on Jupiter's emission for distributions in which the H_2S is not depleted by an NH_4SH cloud.

Figure 7 shows calculated emission spectra with and without cloud opacity included using NH_3 distribution 2b. Substantial opacity is provided by the clouds when values of 0.05 are used for k_{NH_3} and k_{NH_4SH} and the maximum cloud bulk densities from equilibrium condensation models are used. This case corresponds to the maximum possible effect of the absorption from clouds. However, when values of 0.01 for k_{NH_3} and k_{NH_4SH} are used and the cloud bulk densities decreased by a factor of 5, corresponding to a more realistic scenario, the opacity provided by the clouds becomes negligible.

5. Conclusions and Suggestions for Future Work

Using our new formalism for the Ben-Reuven lineshape in model calculations, we find that the millimeter-wave observations of Jupiter *can* adequately be explained using NH_3 opacity alone. Good fits to the observed spectrum are achieved using vertical distributions for NH_3 derived from equilibrium condensations models with deep mixing ratios of $2.5 - 3 \cdot 10^{-4}$ (solar abundance enhanced by a factor of 1.7-2) for NH_3 and less than or equal to the solar abundance ($3.35 \cdot 10^{-4}$ for H_2S.

Gaseous hydrogen sulfide may be providing additional opacity. Observations with greater spectral resolution are needed in order to detect the potential dips in emission due to H_2S and thus distinguish the effects of H_2S opacity from those of NH_3. Absorption by cloud condensates may also be providing opacity. However, due to large uncertainties in the dielectric properties of the condensates and cloud bulk densities, no firm conclusions regarding cloud opacities can be drawn at this time.

More laboratory measurements are needed in order to further evaluate the millimeter-wave and microwave properties of the outer planets. We plan to make measurements of the hydrogen and helium pressure-broadened linewidths of millimeter-wave lines of gaseous hydrogen sulfide in the future. In addition, measurements of the dielectric properties of solid NH_3 and NH_4SH are also needed to accurately assess the effect of cloud condensates on the millimeter-wave spectra of the outer planets.

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Fig. 1. Block diagram of the planetary atmospheres simulator as configured for the measurement of millimeter-wave NH_3 absorption under simulated Jovian conditions.

Fig. 2. Sketch of the Fabry-Perot resonator which operates at 94 GHz (3.2 mm).

Fig. 3. Theoretically derived absorption profiles in a 90% H_2-10% He-0.03% NH_3 mixture at 2 bars and 200K using the Van Vleck Weisskopf lineshape (VVW, dot-dashed line), Zhevakin-Naumov or Gross lineshape (ZN-G, dotted line), Ben-Reuven lineshape as per Berge and Gulkis (BR-BG, dashed line) and Ben-Reuven formalism as given in this paper (BR-JS, solid line).

Fig. 4. Various abundance profiles for NH_3 and H_2S and cloud bulk densities based on equilibrium condesation models. Model 1:$\chi_{H_2S} = 3.35 \cdot 10^{-5}$ (solar), 2a: $\chi_{NH_3} = 2.5 \cdot 10^{-4}$, 2b: $\chi_{NH_3} = 3 \cdot 10^{-4}$; Model 2:$\chi_{H_2S} = 2.2 \cdot 10^{-4}$, 1a: $\chi_{NH_3} = 2.5 \cdot 10^{-4}$, 1b: $\chi_{NH_3} = 3 \cdot 10^{-4}$; $\chi_{H_2O} = 1.23 \cdot 10^{-3}$ (solar). Temperature-Pressure profile calculated with $\chi_{NH_3} = 2.5 \cdot 10^{-4}, \chi_{H_2S} = 3.3 \cdot 10^{-5}, \chi_{H_2O} = 1.0 \cdot 10^{-5}$

Fig. 5. Observed Jovian spectrum (error bars include 10% uncertainty for observations using Mars as calibrator) and computed emission using NH_3 and H_2O opacity only and vertical distributions in Figure 4.

Fig. 6. Observed Jovian spectrum with computed emission using NH_3 distributions 1b and 2a with H_2S distributions 1 and 2 respectively from Figure 4. Dashed line: NH_3 and H_2O opacity only; Solid line: NH_3, H_2O and H_2S opacity; Dotted line NH_3, H_2O and H_2S opacity averaged over a bandwidth of 70 GHz.

Fig. 7. Observed Jovian spectrum with computed emission using NH_3 profile 2b with and without cloud opacity included. Solid line: NH_3 and H_2O opacity only; Dashed line: $k_{NH_3}, k_{NH_4SH} = 0.05$ and maximum bulk densities as shown in Figure 4 (Dotted line below: H_2S opacity added); Dot-dashed line: $k_{NH_3}, k_{NH_4SH} = 0.01$ and maximum bulk densities (same result obtained for $k_{NH_3}, k_{NH_4SH} = 0.05$ and densities decreased by a factor of 5); Dotted line above: $k_{NH_3}, k_{NH_4SH} = 0.01$ and bulk densities decreased by a factor of 5

TABLE I: Absorption summary for NH_3 at 3.2 mm
85.56%H_2, 9.37%He, 5.07%NH_3, T=210K

Date	Press. (atm)	α meas. (dB/km)	α ZN/G	α VVW	α BR-BG	α BR-JS
10/20/88	2.0	115±32	42.3	350.6	117.0	120.8
	2.0	109±32	42.3	350.6	117.0	120.8
	1.7	58±30	30.8	253.9	84.7	87.4
		36±30	30.8	253.9	84.7	87.4
	1.3	0±30	18.2	148.9	49.7	51.1
	1.0	0±30	10.8	88.3	29.4	30.3
10/22/88	2.0	91±30	42.3	350.6	117.0	120.8
10/22/88	2.0	91±30	42.3	350.6	117.0	120.8

TABLE 2. Millimeter-wave observations of Jupiter

λ (mm)	ν (GHz)	T_B (K)	Cal	$\Delta\nu$ (GHz)	Reference
1.0	300	168±8	Mars	102,229	Werner *et al.* (1978)
1.08	279	169.9±5.1	Mars	75	Griffin *et al.* (1986)
1.32	227	170.9±3.9	Mars	70	Griffin *et al.* (1986)
1.32	227	165±8	planets	39	Ulich *et al.* (1984)
1.4	214	[a]148±16	planets	275	Rather *et al.* (1975)
1.40	214	[b]168±11	Mars	210	Courtin *et al.* (1977)
2.00	150	173.3±1.1	Mars	50	Griffin *et al.* (1986)
2.13	141	[a]167±12	abs	1-2	Ulich (1974, 1981)
2.14	140	[a]178±13	abs	1-2	Cogdell *et al.* (1975)
3.09	97	[a]174±10	abs	0.1-0.2	Ulich *et al.* (1973)
3.33	90	172.5±1.4	Mars	1-2	Griffin *et al.* (1986)
3.48	86	179.4±4.7	abs	0.03-0.5	Ulich *et al.* (1980)
3.53	85	[a]166±6	DR21	1-2	Ulich (1974)

[a]Brightness temperatures as given in Berge and Gulkis (1976)

[b]Recalculated with beam correction factor in Ulich *et al.* (1980)

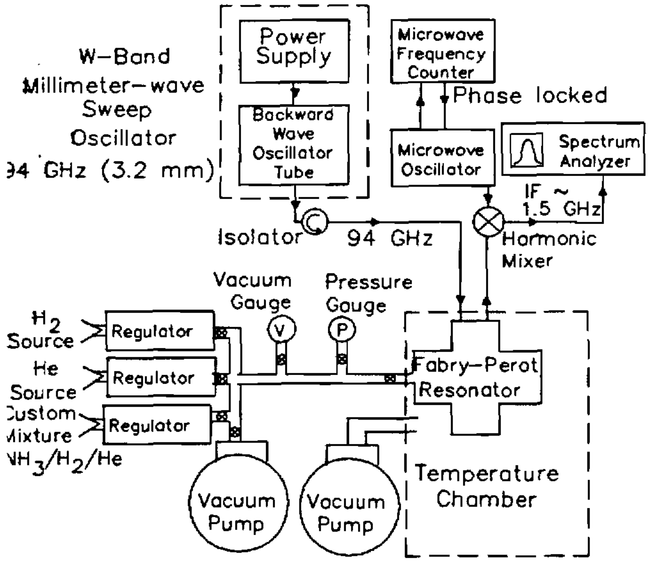

W-Band
Millimeter-wave
Sweep
Oscillator
94 GHz (3.2 mm)
Power
Supply
Backward
Wave
Oscillator
Tube
Microwave
Frequency
Counter
Phase locked
Microwave
Oscillator
Spectrum
Analyzer
IF ~
1.5 GHz
Isolator
94 GHz
Harmonic
Mixer
Vacuum
Gauge
Pressure
Gauge
H_2
Source
Regulator
He
Source
Regulator
Custom
Mixture
$NH_3/H_2/He$
Regulator
Fabry-Perot
Resonator
Temperature
Chamber
Vacuum
Pump
Vacuum
Pump

Figure 1

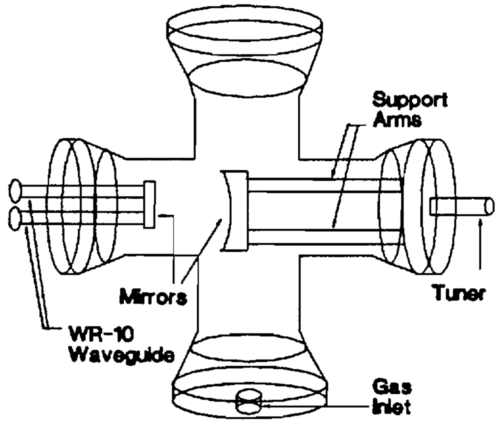
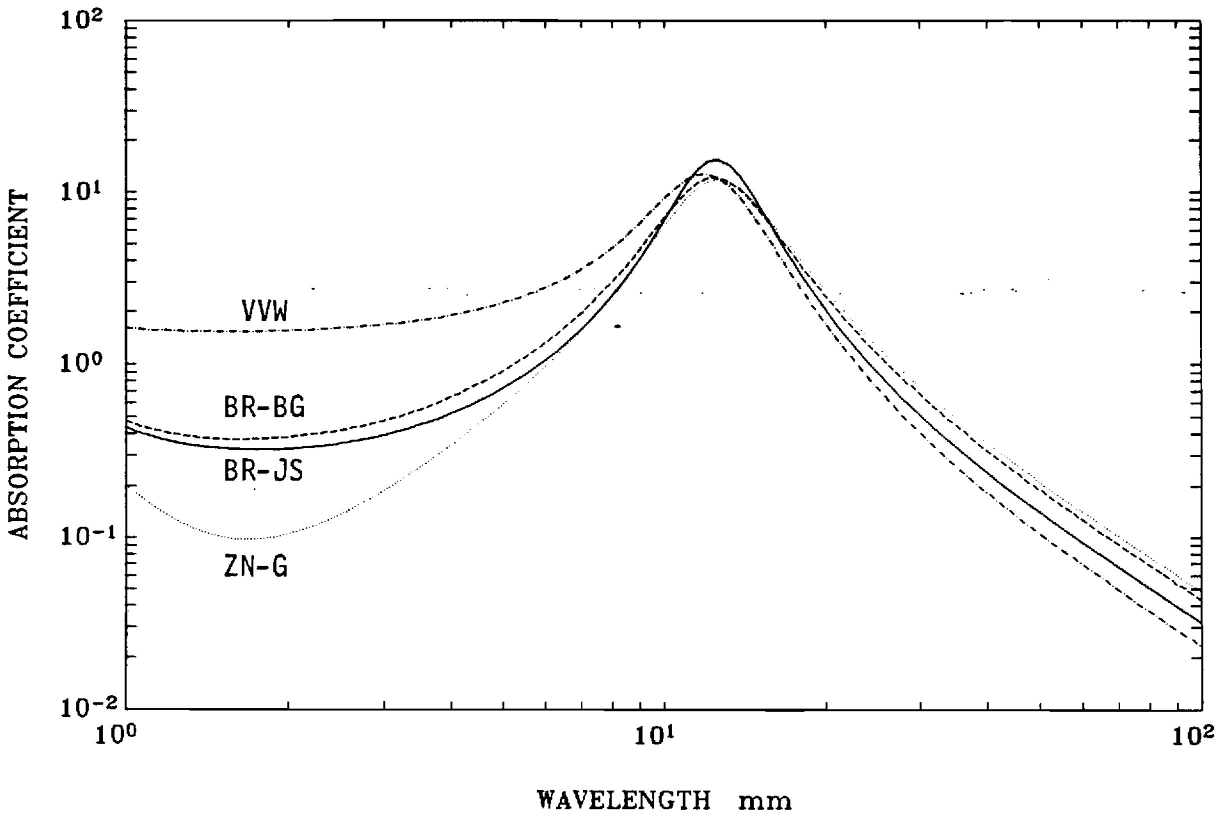
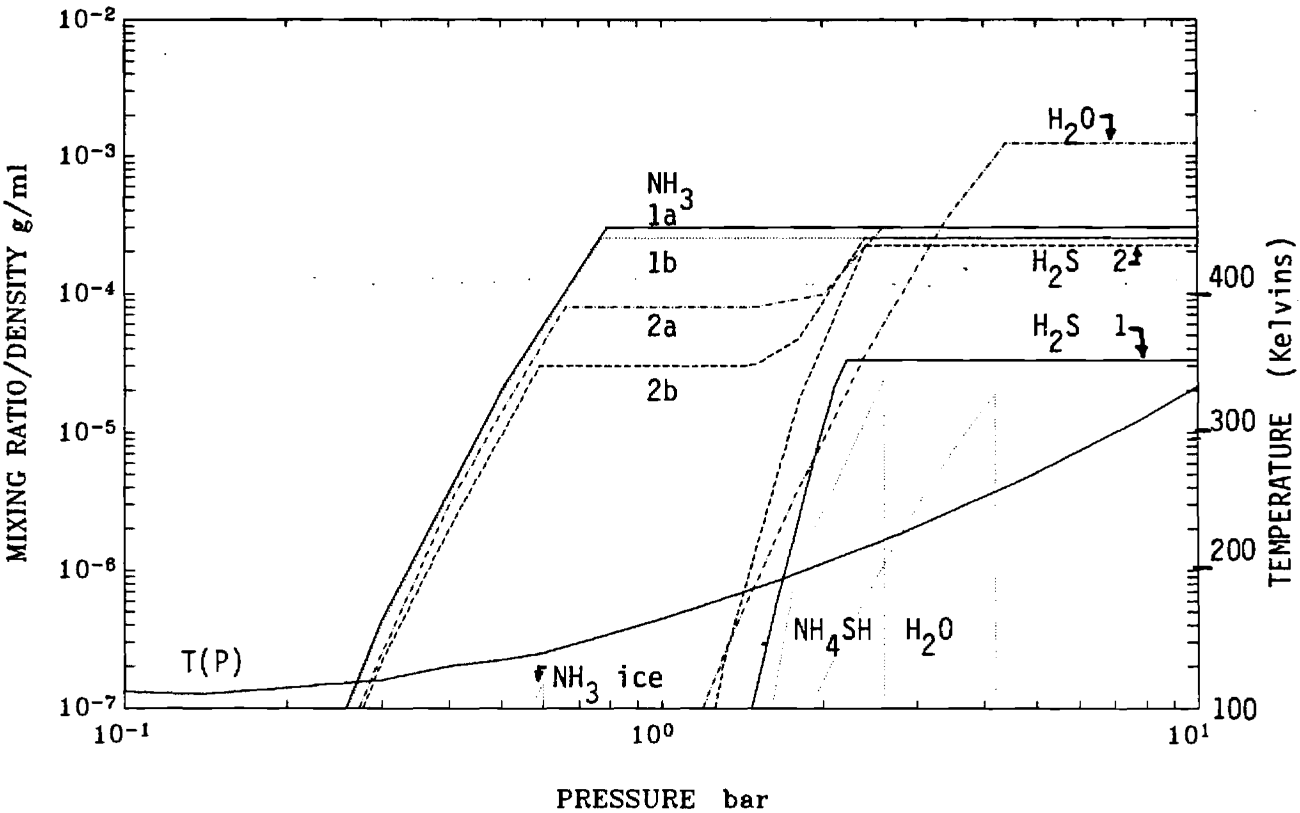


Figure 2



10^2
10^1
10^0
10^{-1}
10^{-2}
ABSORPTION COEFFICIENT
VVW
BR-BG
BR-JS
ZN-G
10^0
10^1
10^2
WAVELENGTH mm

Figure 3



MIXING RATIO/DENSITY g/ml
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-1}
10^{0}
10^{1}
PRESSURE bar
TEMPERATURE (Kelvins)
400
300
200
100
H_2O
NH_3
1a
1b
2a
2b
H_2S 2
H_2S 1
T(P)
NH_3 ice
NH_4SH
H_2O

Figure 4

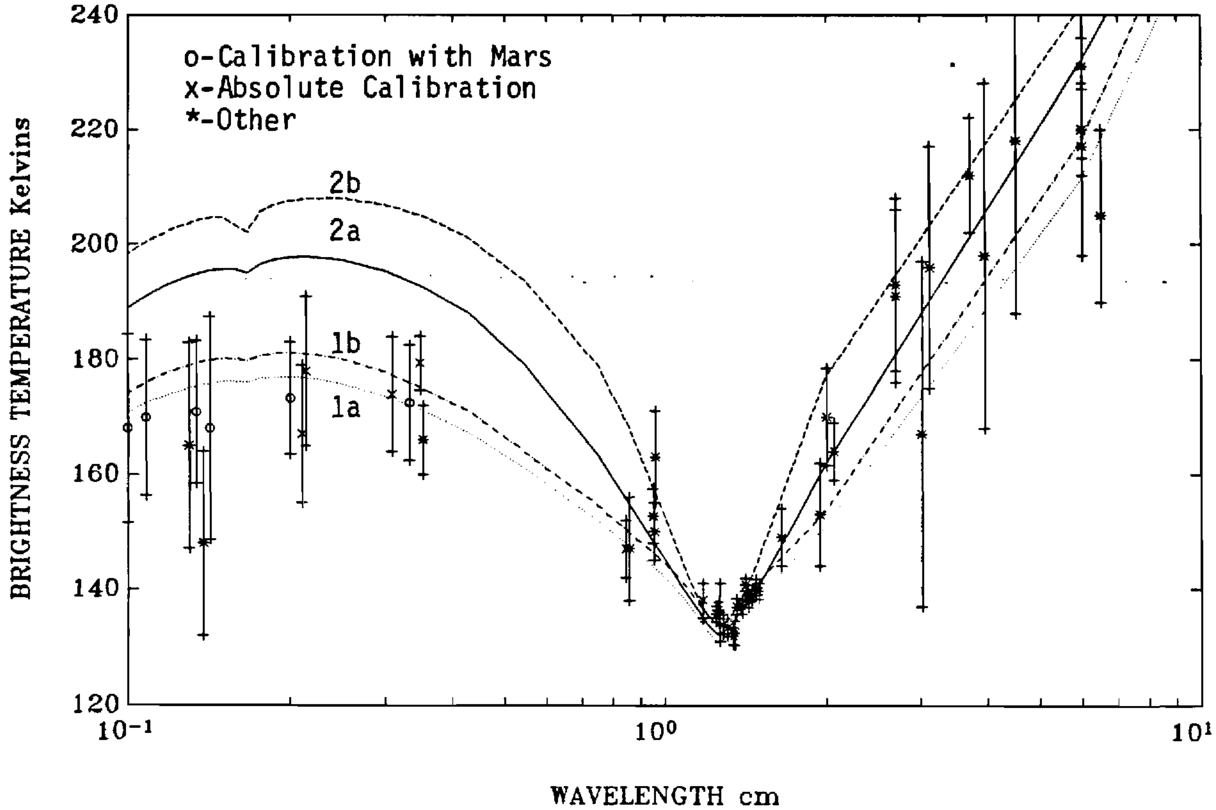
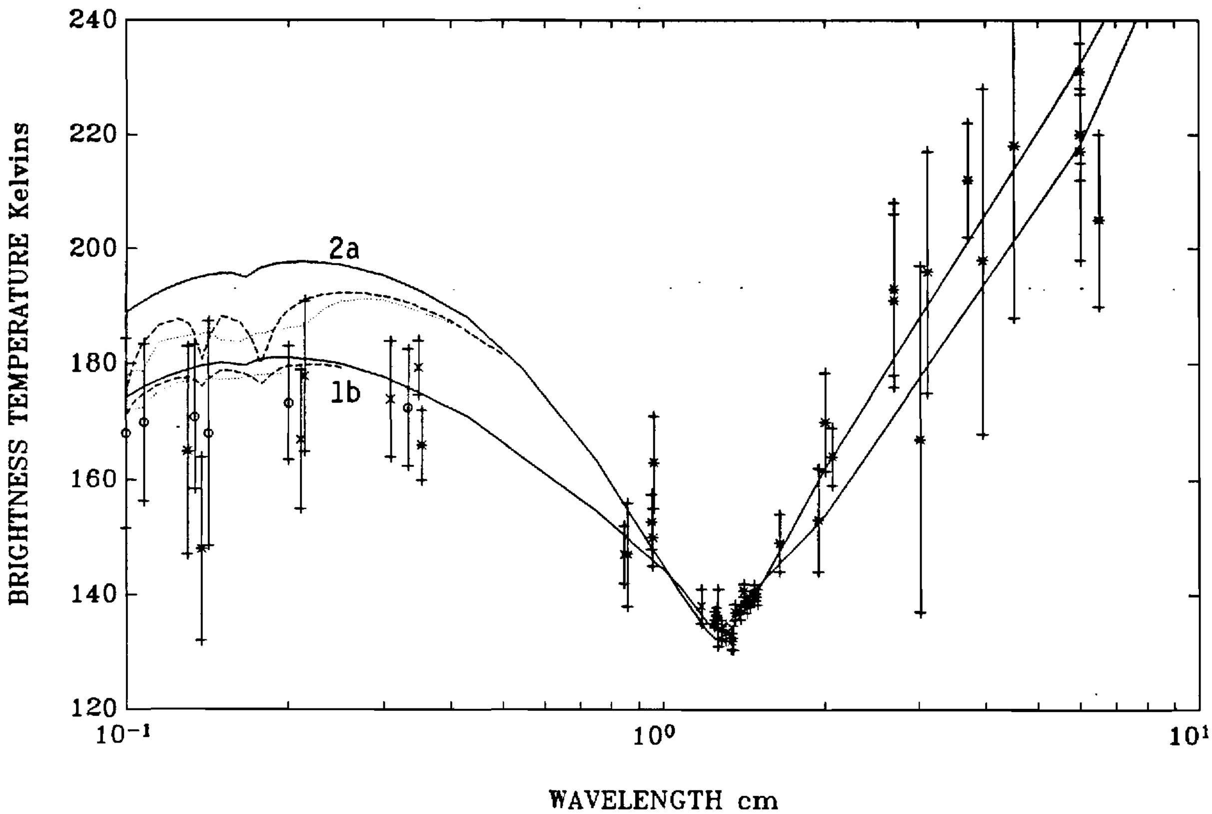
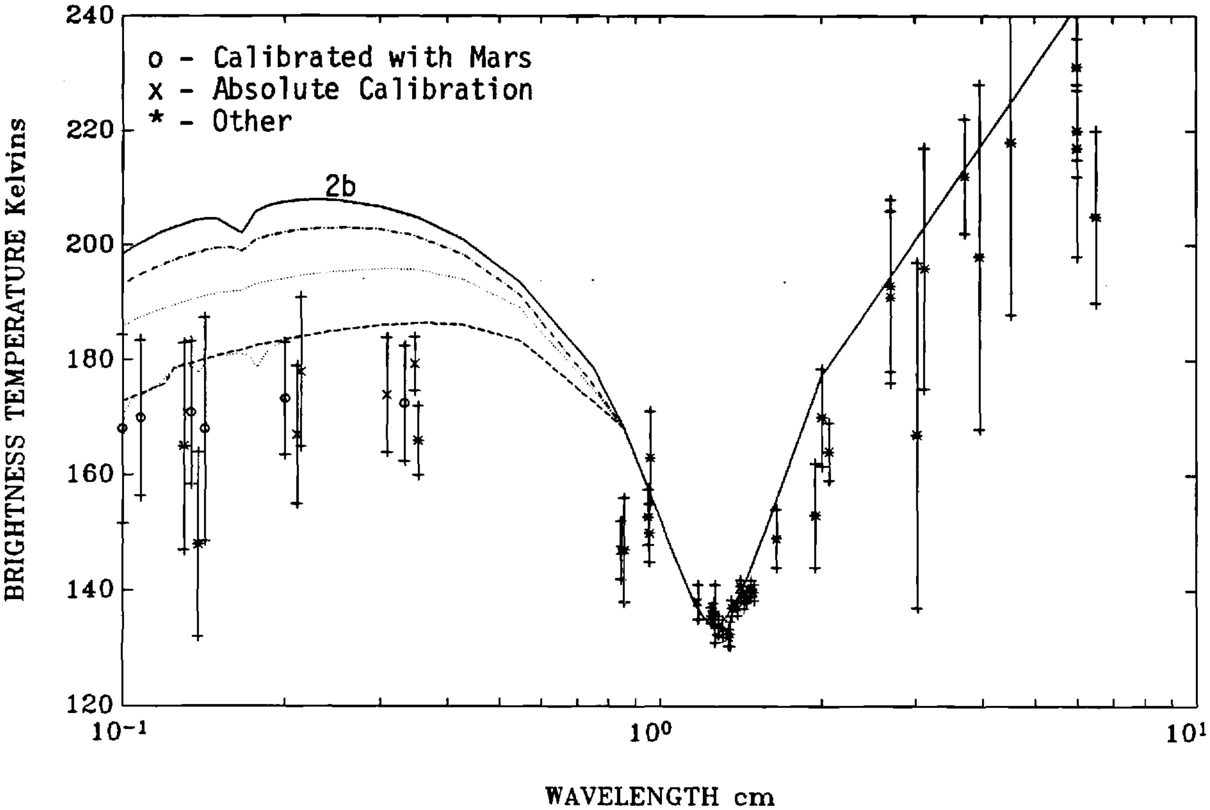

o-Calibration with Mars
x-Absolute Calibration
*-Other
2b
2a
1b
1a
BRIGHTNESS TEMPERATURE Kelvins
240
220
200
180
160
140
120
10^{-1}
10^{0}
10^{1}
WAVELENGTH cm

Figure 5



240
220
200
180
160
140
120
BRIGHTNESS TEMPERATURE Kelvins
2a
1b
10^{-1}
10^{0}
10^{1}
WAVELENGTH cm

Figure 6



240
220
200
180
160
140
120
BRIGHTNESS TEMPERATURE Kelvins
o - Calibrated with Mars
x - Absolute Calibration
* - Other
2b
10^{-1}
10^{0}
10^{1}
WAVELENGTH cm

Figure 7

LABORATORY MEASUREMENT OF THE MILLIMETER-WAVE PROPERTIES OF LIQUID SULFURIC ACID (H_2SO_4).

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Abstract. Recent observations of the millimeter-wave (2.6 mm) emission from Venus have shown significant variations in its continuum flux emission (de Pater et al., 1991). Some of this change in emission may be attributed to variability in the abundance of Venus cloud constituents; specifically H_2SO_4 condensates. The ability to judge the validity of this assumption requires knowledge of the electrical properties of the absorbing condensate at millimeter-wave frequencies (30<f<300 GHz). In order to accurately model the effect of the condensates on the flux emission from Venus, a determination of the dielectric properties of liquid H_2SO_4 is essential. As a result, laboratory measurements of the complex dielectric constant of liquid sulfuric acid between 30-40 and 90-100 GHz have been performed.

The methodology and the results are reported in this paper along with a calculation of the absorption of H_2SO_4 droplets under Venus-like conditions. In addition, this paper discusses the effects of these condensates on the variation in the flux-emission of Venus and compares the effect of H_2SO_4 droplets with other absorbers in the atmosphere of Venus such as gaseous SO_2. We conclude that this condensate does affect the brightness temperature of Venus and its effect cannot be omitted in future modeling of the atmosphere of Venus.

I. Introduction

Recent observations of the millimeter-wave emission of Venus at 112 GHz (2.6 mm) have shown a 30 K variation in the observed flux emission as reported by de Pater et al. (1991). These emission variations may be attributed to variations in the abundance of absorbing constituents present in the middle atmosphere of Venus. Such constituents include gaseous H_2SO_4, SO_2, CO_2 and liquid sulfuric acid in the form of cloud condensate. (Detailed description regarding the presence of these constituents may be found in Steffes and Eshleman (1982), Steffes (1985), and Steffes et al. (1990)) Among these constituents, gaseous CO_2 is considered to be the primary absorber in the atmosphere of Venus. However, the CO_2 abundance variability is considered to be low and therefore cannot account for the measured variability in emission.

Recently, de Pater et al. (1991) suggested that this variability may be attributed to the variation in the abundance of the cloud condensate (i.e, liquid sulfuric acid). In order to evaluate this hypothesis, a knowledge of the dielectric properties of liquid sulfuric acid at millimeter-wave frequencies is needed so as to determine the expected absorptivity from such condensate, and hence the effect of this condensate on the emission spectrum of Venus. Estimation of the absorption of this condensate at millimeter-wave frequencies is not straightforward since no laboratory measurements of the dielectric constant of liquid H_2SO_4 have been previously reported at millimeter wavelengths. Although the dielectric properties of liquid H_2SO_4 at microwave frequencies have been measured (Cimino, 1982), direct extrapolation of these results into the millimeter-wave region can lead to ambiguous results.

This paper describes the methodology and the results of laboratory measurements of the millimeter-wave properties of liquid sulfuric acid. These measurements represent the first time that measurements of the millimeter-wave dielectric property of liquid sulfuric acid have been reported.

In this paper, we describe measurements conducted at 30-40 and 90-100 GHz, using two different concentrations of liquid H_2SO_4. In addition, the measured data is used to compute the expected opacity of H_2SO_4 condensates and their effects on the millimeter-wave emission from Venus.

II. Experimental Approach

The approach used in the measurement of the dielectric properties of liquid sulfuric acid at millimeter-wave frequencies is similar to that described by Moore et al. (1991). The experiment employs a free space transmission setup as indicated in Figure 1. In this configuration, the sample is placed between the transmitting and receiving antennas. In addition, optical lenses are used to focus the energy on the surface of the sample. The lenses and the two horn antennas are mounted on an adjustable rail to allow accurate positioning of these components with respect to the sample. Although the sample holder is designed to rotate to change the incidence angle of the transmitted wave, our measurements were performed at a normal incidence with respect to the sample.

In order to use this system for measuring the complex dielectric constant of liquids, a suitable cell had to be designed to hold the liquid sulfuric acid and to minimize the reaction of the acid with the cell walls. A sketch of the cell used is shown in Figure 2 where the cell walls are manufactured from high grade Teflon. The thickness of the cell walls and the liquid sample are chosen so that an adequate signal level can be measured by the receiving antenna. A thickness of 1270 μm is chosen as an appropriate value for the walls and liquid sample. In addition, the variation in the thickness of the cell walls is minimized in order to insure a uniform sample thickness (±25.4 μm is achieved).

A block diagram of the electrical components used to measure the dielectric constant of liquid sulfuric acid between 90-100 GHz is shown in Figure 3. A similar system employing different antennas and lenses along with the appropriate power source is used for frequencies between 30.0 and 40.0 GHz. In both configurations, the system employs a digital computer to automate the measurement process and to control the Hewlett-Packard 8510 network analyzer used to measure the transmission coefficient of the liquid sample.

III. Experimental Procedure

The first step in the measurement process is the calibration of the system (without the sample). In addition, a check on the accuracy of the calibration process is performed by measuring the dielectric constant of a single sheet of material and comparing the measured values with published data. Once the calibration is satisfactory, the filled cell is mounted and measurement of the transmission coefficient of the liquid, $(S_{21})_{measured}$, as function of frequency is performed. The results of such measurements are then stored on a magnetic disk for later analysis.

As stated earlier, the measurement of the complex permittivity ($\epsilon_r = \epsilon'_r - j\epsilon''_r$) of liquid sulfuric acid was performed at two different frequency bands covering 30-40 and 90-100 GHz. The measurements of the complex dielectric constant of two samples of liquid sulfuric acid having 99% and 85% concentration by weight were performed. The latter concentration was equivalent to the estimated concentration of sulfuric acid in the clouds of Venus. In addition, the measurement of the dielectric constant of distilled water was performed in order to check the accuracy of our measurement process. In this case, a close agreement between our measurements and those previously reported (Oguchi, 1983) was obtained.

IV. Determination of ϵ_r

The determination of the complex dielectric constant of the liquid under test requires careful characterization of the geometry of the cell used and the determination of the theoretical transmission coefficient of that cell. A sketch of the liquid cell used in our setup is shown in Figure 4 where medium I and III denote the teflon walls of thickness d while medium II represents the liquid under test with thickness t. For the geometry shown in Figure 4, a composite scattering matrix representing the three media and the corresponding interfaces can be written as,

$$[S]_T = [S]_{12}[S]_I[S]_{23}[S]_{II}[S]_{34}[S]_{III}[S]_{45} \tag{1}$$

where $[S]_T$ is a 2x2 matrix relating the incoming and outgoing wave amplitudes in medium 1 and 5 as shown Figure 4. Another important quantity is the propagation constant of an electromagnetic wave in medium i which can be expressed as,

$$k_i = 2\pi f \frac{\sqrt{\mu_{ri}\epsilon_{ri}}}{c} \tag{2}$$

where f denotes the frequency, c is the speed of light in free space and ϵ_{ri} and μ_{ri} are respectively the relative complex permittivity and permeability of medium i. These two complex quantities can be expressed as,

$$\mu_{ri} = \mu'_{ri} - j\mu''_{ri} \tag{3}$$

and

$$\epsilon_{ri} = \epsilon'_{ri} - j\epsilon''_{ri}\,. \tag{4}$$

Since liquid sulfuric acid does not posses magnetic properties, μ_{ri} is equal to μ_o.

The composite scattering matrix $[S]_T$ can then be written as a function of the propagation constants of the three media and their respective thicknesses. Since the dielectric constant of Teflon is well known ($\epsilon_{rI} = \epsilon_{rIII} = 2.0 - j.02$), $[S]_T$ can then be written as a function $\mathscr{F}$ such that,

$$[S]_T = \mathscr{F}(k_{II}, t, d) \tag{5}$$

where k_{II} is the propagation constant in medium II as expressed in equation (2).

Once $[S]_T$ has been determined, one can solve for the propagation constant of medium II (k_{II}) by minimizing,

$$(S_{21})_{measured} - (S_{21})_T \tag{6}$$

where $(S_{21})_{measured}$ is the measured transmission coefficient of the filled cell while $(S_{21})_T$ is the theoretically calculated transmission coefficient obtained from the matrix $[S]_T$. This minimization process is carried out using a root finder program based on Newton's method and an initial guess for k_{II}. Once a satisfactory value of k_{II} has been reached in accordance with (6), the complex dielectric constant of the liquid under test can be determined using,

$$\epsilon_{rII} = (k_{II}/k_o)^2 \qquad (7)$$

where k_o denotes the propagation constant in free space.

V. Experimental Results

The results of the measurements of the complex dielectric constant of liquid sulfuric acid at frequencies between 30.0 and 40.0 GHz are shown in Figures 5 and 6. Figure 5 shows the real part of the relative dielectric constant (ϵ'_{rII}) as function of frequency for 99.0% and 85.0% concentrations (by weight) of sulfuric acid in addition to ϵ'_{rII} for water (room temperature). Figure 6 shows the imaginary part of ϵ_{rII} (ϵ''_{rII}) as function of frequency for the same liquids.

Similarly, the results of the measurement of the complex dielectric constant at 90.0-100.0 GHz are shown in Figures 7 and 8. The error bars shown in these four figures represent $\pm 1\sigma$ variation in the calculated values of ϵ'_{rII} and ϵ''_{rII} resulting from uncertainties in the thickness t of $\pm 25.4\,\mu m$. Hence, these error bars do not include uncertainties due to instrumental errors which are on the order of ±3% of the reported mean values.

In order to apply the measured data in modeling the emission from the atmosphere of Venus, a relationship between the complex dielectric constant, physical parameters of the condensate (size and mass content) and the expected absorptivity of such a condensate is needed. Regarding the physical parameters of the condensate, extensive studies have been performed using data from several entry probes (Knollenberg and Hunten, 1980). Droplets sizes of 25 microns with an approximate mass content of 50 mg/m^3 provide a conservative upper limit for the physical parameters of the cloud condensate. As a result, the expected absorptivity can be evaluated using a Rayleigh absorption model (that is , $|(\epsilon_r)^{1/2}\chi|<1$, where $\chi=2\pi r(\epsilon'_r)^{1/2}/\lambda$ and r is the radius of the droplets, (Ulaby,1981)) where the absorption coefficient, α, can be expressed as,

$$\alpha = \frac{246 M \epsilon''_r}{\rho\lambda[(\epsilon'_r+2)^2+(\epsilon''_r)^2]}\ (\mathrm{dB/km}) \qquad (8)$$

where ρ is the density of the liquid and M is the bulk density of the clouds in the same units, λ is the wavelength in km and ϵ'_r and ϵ''_r are, respectively, the real and imaginary parts of the complex dielectric constant of the liquid. (Note, for example, that an attenuation constant or absorption coefficient or absorptivity of 1 Neper km^{-1} = 2 optical depths per km (or km^{-1})= 8.686 dB km^{-1}, where the first notation is the natural form used in electrical engineering, the second is the usual form in physics and astronomy, and the third is the common (logarithmic) form. The third form is often used in order to avoid a possible factor-of-2 ambiguity in meaning).

The calculated values of the absorption coefficient of liquid sulfuric acid for 85% and 99% concentration by weight (in addition to those for water) are shown in Figures 9 and 10. In these figures, the absorption of H_2SO_4 and H_2O droplets have been calculated for the same volume density (M/ρ ratio is constant for both liquids). A close examination of these results indicate that the expected absorption for 85% concentrated sulfuric acid droplets is at least 20% higher than that expected from water. This indicates that the absorptivity of sulfuric acid may have an effect on the variation of the millimeter-wave emission from Venus.

VI. Discussion

The key result of our work has been the determination of the complex dielectric constant of liquid sulfuric acid at the concentration expected for the clouds of Venus. Our results show that the expected absorption of liquid H_2SO_4 is at least 20% higher than that of water condensate. Thus the absorption from liquid sulfuric acid may affect the millimeter-wave emission of Venus. In order to determine the effect of H_2SO_4 droplets on the emission of Venus, our data has been incorporated into a radiative transfer model of the atmosphere of Venus. This model calculates the effects of several constituents (gaseous SO_2, CO_2 and H_2O) on the brightness temperature of Venus at millimeter wavelengths. Although the absorptivities of some of the constituents have not been measured at millimeter wavelengths, extensive analytical calculations regarding their absorptivities have been reported. In addition, the absorption of gaseous sulfuric acid is not included in our model since no measured or calculated data have been reported at these high frequencies.

Preliminary results from the radiative transfer model indicate that liquid H_2SO_4 does indeed affect the brightness temperature of Venus at 95 GHz. A decrease of 2 K is indicated for a uniform cloud layer in the 48-50 km altitude range similar to that described by Knollenberg and Hunten (1980). This decrease in brightness temperature is comparable with that attributable to gaseous SO_2 (SO_2 is assumed to be uniformly mixed below 48 km altitude and exponentially decreasing above). However, this 2 K variation in brightness temperature is much less than the observed variation in the millimeter-wave emission of Venus. Recently, de Pater (1991) reported observing a variation of 30 K in the brightness temperature of Venus at 112 GHz.

In order to determine which constituents are responsible for the reported variations in the emission of Venus, a complete knowledge of the millimeter-wave properties of all constituents (especially gaseous H_2SO_4) is necessary.

VII. Conclusion

Laboratory measurements of the complex dielectric constant of liquid sulfuric acid at 30-40 and 90-100 GHz have been performed on two different samples of H_2SO_4 with 85% and 99% concentration by weight. Using the measured data and the physical parameters of sulfuric acid condensate in the clouds of Venus, the absorptivity of H_2SO_4 condensate has been determined.

The calculated absorptivity of liquid sulfuric acid has been incorporated into a radiative transfer model of Venus in order to determine the effects of H_2SO_4 droplets on the variability in the millimeter-wave emission from Venus. The results of our model indicate that the cloud condensate does have an effect on the emission of Venus. However, the calculated decrease in brightness temperature is well below the observed decrease in brightness temperature (de Pater, 1991). As a result, this observed variability may not be completely due to sulfuric acid droplets.

Other constituents such as gaseous H_2SO_4 may also affect the observed variations in the brightness temperature. The effect of this constituent is not fully known since no measurement of the absorption of gaseous sulfuric acid have been performed at millimeter-wave frequencies. Hence, one can only speculate whether this variability can be completely due to liquid sulfuric acid.

Currently, measurements of the absorption of gaseous sulfuric acid and SO_2 at millimeter-wavelengths are being performed under Venus-like conditions. The results from our measurements will be incorporated in our model in order to determine the effects of these constituents on the observed variability in the brightness temperature of Venus.

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Fahd and Steffes: Dielectric constant of H_2SO_4

Fahd and Steffes: Dielectric constant of H_2SO_4

Fig. 1. Sketch of free space measurement system.

Fig. 2. Sketch of the liquid cell used in the free space measurement of the dielectric constant of sulfuric acid.

Fig. 3. Block diagram of the free space measurement setup, as configured for measurements of the millimeter-wave complex dielectric constant of liquid sulfuric acid.

Fig. 4. Detailed sketch of the liquid cell representing various media and their respective interfaces.

Fig. 5. The measured real part of the complex dielectric constant of water and sulfuric acid for frequencies between 30 and 40 GHz at room temperature. Error bars indicate $\pm 1\sigma$ variation in the measured quantities about the mean values.

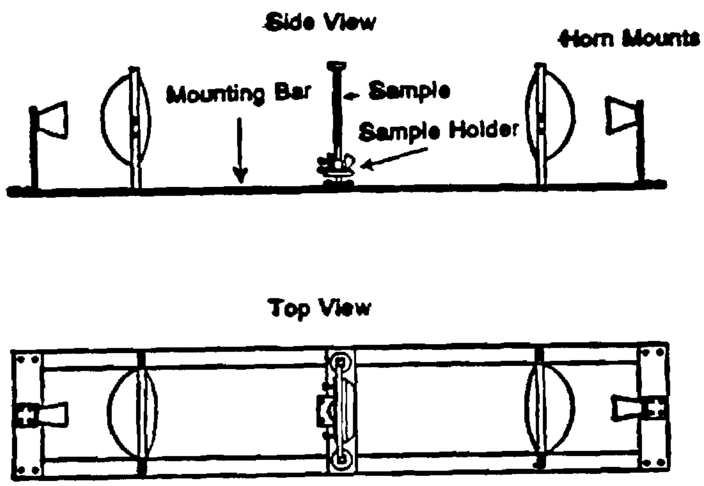
Fig. 6. The measured imaginary part of the complex dielectric constant of water and sulfuric acid for frequencies between 30 and 40 GHz at room temperature. Error bars indicate $\pm 1\sigma$ variation in the measured quantities about the mean values.

Fig. 7. The measured real part of the complex dielectric constant of water and sulfuric acid for frequencies between 90 and 100 GHz at room temperature. Error bars indicate $\pm 1\sigma$ variation in the measured quantities about the mean values.

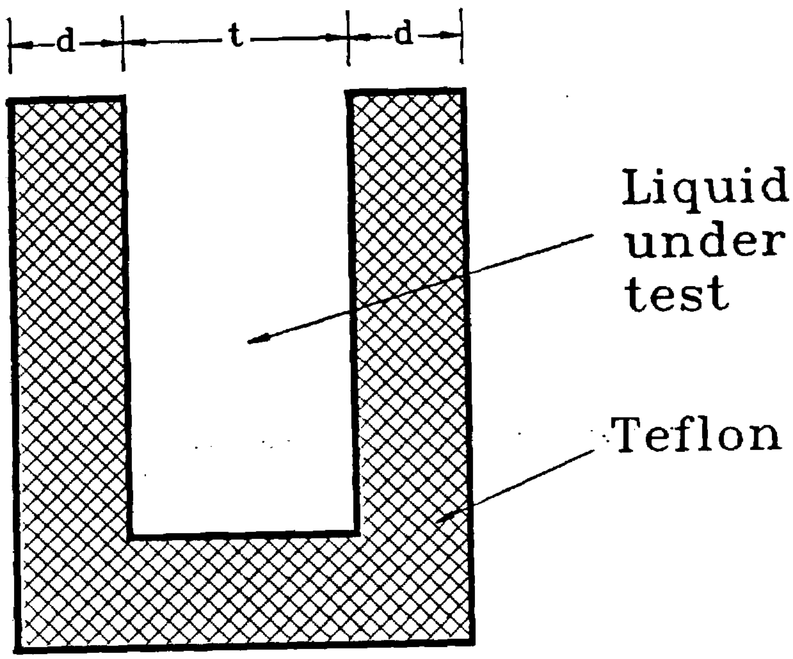
Fig. 8. The measured imaginary part of the complex dielectric constant of water and sulfuric acid for frequencies between 90 and 100 GHz at room temperature. Error bars indicate $\pm 1\sigma$ variation in the measured quantities about the mean values.

Fig. 9. Comparison of attenuation (dB/km) from an 85% (by weight) sulfuric acid solution with that from water droplets for a particular volume fraction (volume of particles/total volume = 2.82×10^{-8}) for frequencies between 30 and 40 GHz.

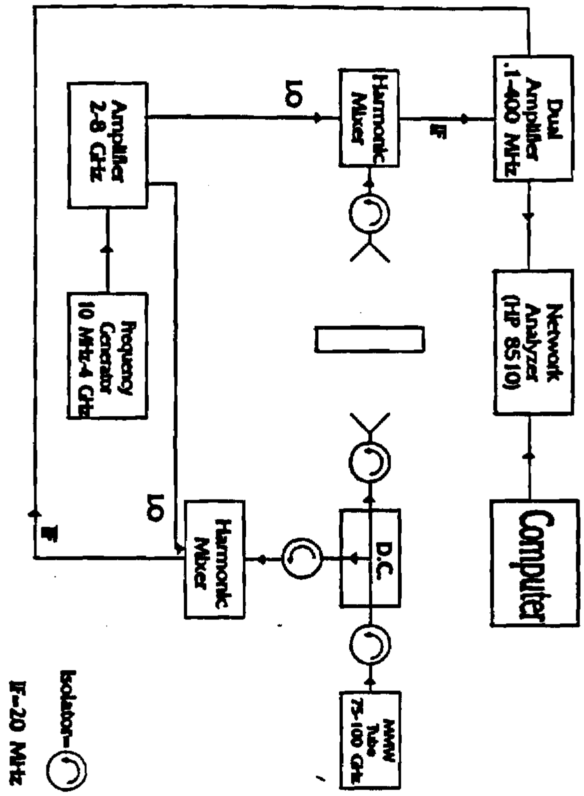
Fig. 10. Comparison of attenuation (dB/km) from an 85% sulfuric acid solution with that from water droplets for a particular volume fraction (volume of particles/total volume = 2.82×10^{-8}) for frequencies between 90 and 100 GHz.



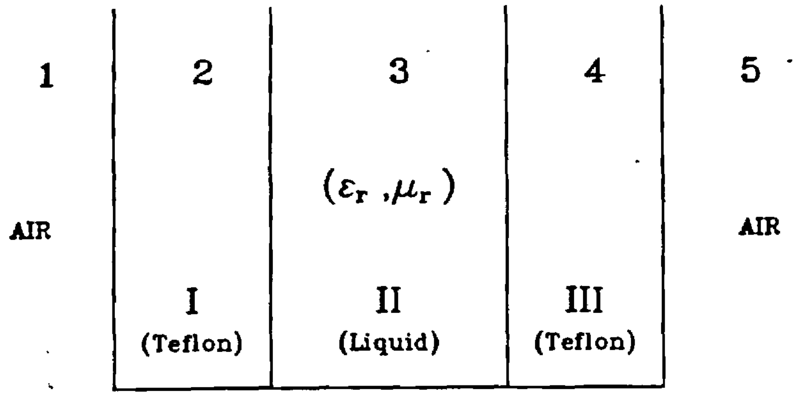
FAHD AND STEFFES, FIGURE 1



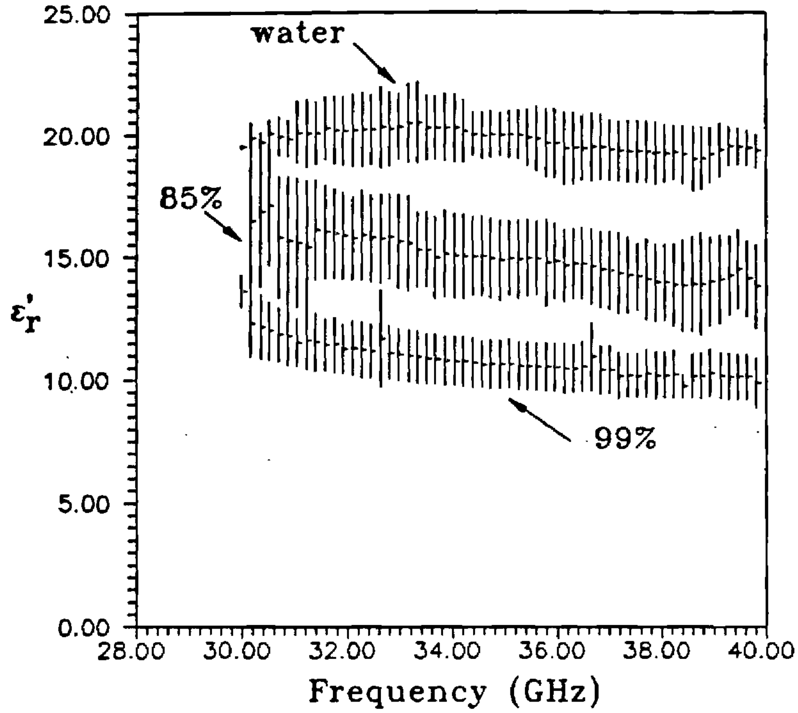
FAHD ANS STEFFES, FIGURE 2



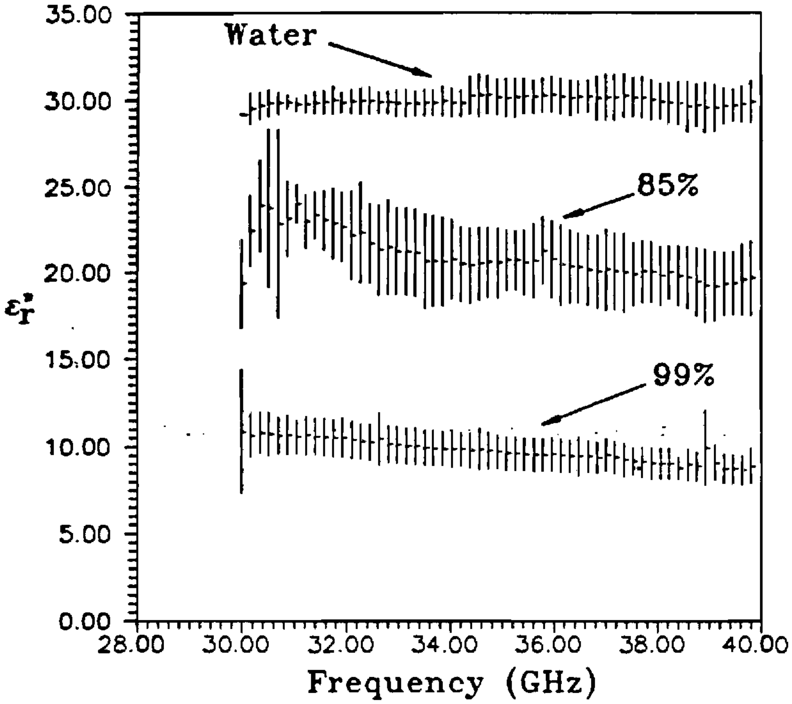
FAHD AND STEFFES, FIGURE 3



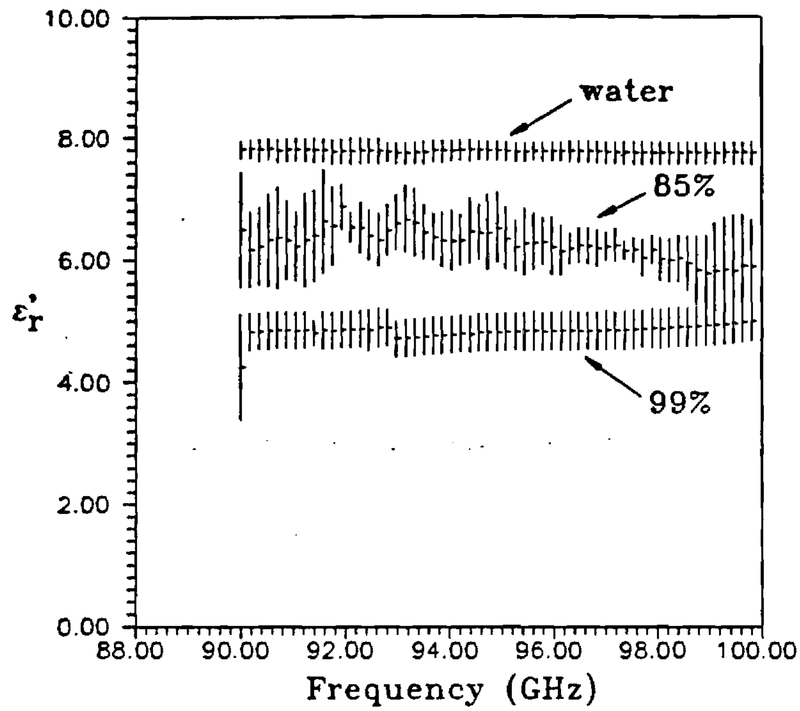
FAHD AND STEFFES, FIGURE 4



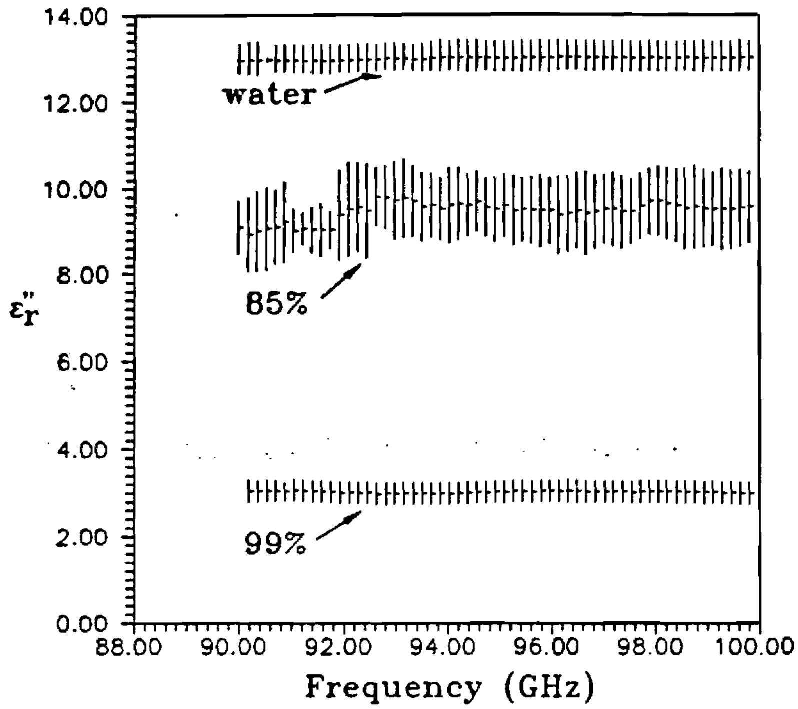
FAHD AND STEFFES, FIGURE 5



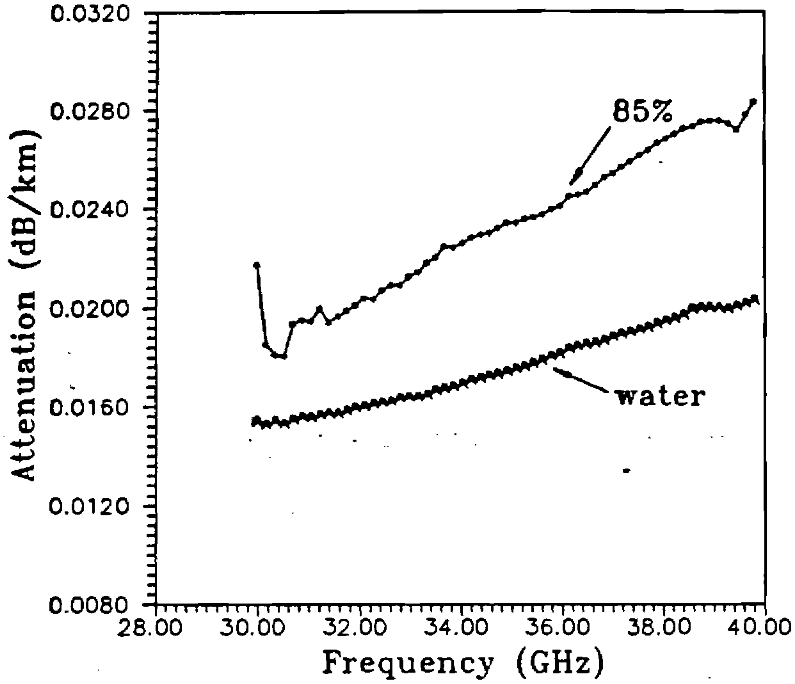
FAHD AND STEFFES, FIGURE 6



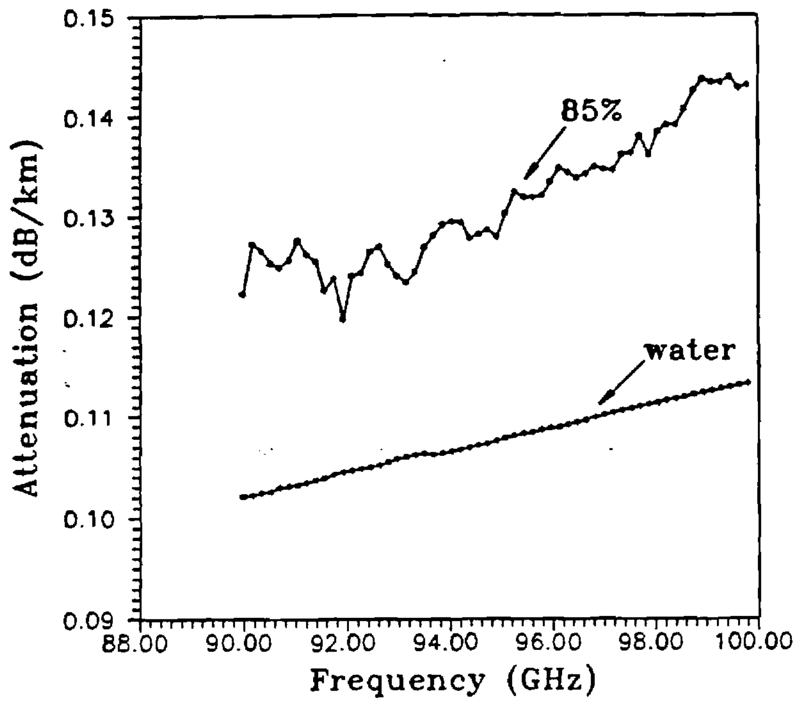
FAHD ANS STEFFES, FIGURE 7



FAHD AND STEFFES, FIGURE 8



FAHD AND STEFFES, FIGURE 9



FAHD AND STEFFES, FIGURE 10

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16

RENEWAL PROPOSAL

AND

ANNUAL REPORT
(Includes Semiannual Status Report #16)

TO THE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

for

GRANT NAGW-533

LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

Paul G. Steffes, Principal Investigator

Report Period: November 1, 1990 through October 31, 1991
Proposed Renewal Period: November 1, 1991 through October 31, 1992
Requested Funding Level: $65,000

Submitted by

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July 1991

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I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing atmospheric constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or using laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. For example, laboratory measurements performed by Joiner et al. (1989), under Grant NAGW-533, have shown that the millimeter-wave capacity of ammonia between 7.5 mm and 9.3 mm and also at the 3.2 mm wavelength is best described by a different lineshape than was previously used in theoretical predictions. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements and to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

A key activity over the past grant year has continued to be laboratory measurement of the microwave and millimeter-wave properties of the simulated atmospheres of the outer planets and their satellites. However, we have also focussed on development of a radiative transfer model of the Jovian atmosphere at wavelengths from 1 mm to 10 cm. This model utilizes our laboratory data and has also been used to evaluate the need for laboratory measurements of other possible absorbers. This modeling effort has led us to conduct a laboratory measurement of the millimeter-wave opacity of hydrogen sulfide (H_2S) under simulated Jovian conditions. Since our modeling effort suggested that it was possible to determine limits on the abundance of H_2S in the atmosphere of Jupiter using a medium resolution observation at 1.4 mm, an observation of Jupiter was conducted in November, 1990, from the Caltech Submillimeter Observatory (CSO) in Hawaii. Descriptions of the modeling effort, the laboratory experiment, and the observation are given in two papers. The first is entitled "Modeling of the Millemeter-Wave Emission of Jupiter Utilizing Laboratory Measurements of Ammonia (NH_3) Opacity" by Joiner and Steffes (1991), and has been accepted for publication in the Journal of Geophysical Research: Planets. (A preprint of this paper was included with Semiannual Status Report #15 for this grant.) The second paper has been submitted for publication n the IEEE Transactions on Microwave Theory and Techniques (special issue commemorating the International Space Year), and is entitled "Search for Sulfur (H_2S) on Jupiter at Millimeter Wavelengths" by Joiner et al. (1991). (A preprint is attached as Appendix D.)

An important source of information regarding the Venus atmosphere is the increasing number of high-resolution millimeter-wavelength emission measurements which have been recently conducted. (See, for example, de Pater et al., 1991)

Correlative studies of these measurements with Pioneer-Venus radio occultation measurements (Jenkins and Steffes, 1991) and our longer wavelength emission measurements (Steffes et al., 1990) have provided new ways for characterizing temporal and spatial variations in the abundance of both gaseous H_2SO_4 and SO_2, and for modeling their roles in the subcloud atmosphere. However, unambiguous results require that we have dependable knowledge of the microwave and millimeter-wave opacity of gaseous and liquid H_2SO_4, and of gaseous SO_2 under Venus conditions.

While some laboratory measurements of the microwave absorption properties of gaseous SO_2 under simulated Venus conditions were made at 13 cm and 3.6 cm wavelengths by Steffes and Eshleman (1981), no measurements have been made at shorter wavelengths. Since the 1.35 cm wavelength appeared to be one of the better wavelengths for measuring the sub-cloud SO_2 abundance (Steffes et al., 1990), we have conducted laboratory measurements of the 1.35 cm (and 13 cm) opacity of gaseous SO_2. The results and application of this work were discussed in the previous Annual Report (includes Seminannual Status Report #14) for Grant NAGW-533 (11/1/89 - 10/31/90). However, over this past grant year we have also conducted laboratory measurements of the absorptivity of gaseous SO_2 at the 3.2 mm wavelength under simulated Venus conditions. These measurements were described in Semiannual Status Report #15 for this grant. Likewise, we have recently completed laboratory measurements of the millimeter-wave dielectric properties of liquid H_2SO_4, in order to model the effects of the opacity of the clouds of Venus on the millimeter-wave emission spectrum. This laboratory experiment and its results are described in a paper entitled "Laboratory Measurement of the Millimeter-Wave Properties of Liquid Sulfuric Acid (H_2SO_4)"

by Fahd and Steffes (1991), which has been accepted for publication in the Journal of Geophysical Research: Planets. (A preprint of this paper was included with Semiannual Status Report #15 for this grant.) In addition, we have implemented a millimeter-wavelength radiative transfer model for Venus, which is described in Section III of this report. It employs results from our laboratory measurements for the millimeter-wave properties of gaseous and liquid constituents of the Venus atmosphere.

We have also been successful in the past grant year in obtaining permission from the Magellan Project to conduct a radio occultation experiment with the Magellan Spacecraft. This will be the first atmospheric work conducted with Magellan and will probe the atmosphere to deeper levels than was possible with the less powerful Pioneer-Venus Orbiter radio transmission system. This experiment will be conducted on October 5, 1991, and will consist of three entry occultation experiments. A description of this experiment is included in Section III of this report.

Early in the next grant year, we intend to complete the analysis of our observations of the 1.4 mm emission spectrum of Jupiter. By using the results of our laboratory measurements of the 1.4 mm opacity of gaseous H_2S, combined with our radiative transfer model already developed for Jupiter, we hope to establish limits on the abundance and distribution of gaseous H_2S in the Jovian atmosphere. The result of this study will be reported in a Ph.D. dissertation by Joanna Joiner, which will be submitted as a Technical Report. We will also complete construction of the laboratory apparatus for measurement of the millimeter-wave opacity from gaseous H_2SO_4 under simulated Venus conditions. We will then complete measurements of the millimeter-wave opacity of gaseous H_2SO_4, and apply the results to our radiative transfer model in order to better explain reported spatial variations in the millimeter-wave emission from Venus (de Pater et al., 1991). We will also begin analysis of the radio occultation data obtained from Magellan on October 5, 1991. This will provide much more accurate and deeper profiles of the abundance of gaseous H_2SO_4 in the Venus atmosphere.

Finally, we intend to pursue an integrated multi-spectral analysis of Venus atmospheric data employing: 1) recent Pioneer-Venus radio occultation data for 13 cm opacity in the Venus atmosphere (ref. Jenkins and Steffes, 1991), as well as more recent data from both Pioneer-Venus and Magellan radio occultation experiments; 2) recent earth-based observations of the microwave (ref. Steffes et al., 1990) and millimeter-wave (ref. de Pater et al., 1991) emission from Venus, and 3) recent earth-based and spaced-based observations of the I.R. emission from Venus. Our study will also establish requirements for additional laboratory measurements, especially in the I.R.

II. OUTER PLANETS STUDIES

We have observed Jupiter at multiple wavelengths near 1.4 mm in an attempt to detect or place upper limits on the abundance of gaseous hydrogen sulfide (H_2S) in Jupiter's troposphere. Using Mars as the standard for calibration, we have derived a reliable brightness temperature for Jupiter at this wavelength. We have also conducted a laboratory measurement of the 1.4 mm absorption from H_2S in a simulated Jovian atmosphere (predominantly H_2, with small amounts of He and H_2S). We have applied the results of this experiment to radiative transfer models which are used predict the millimeter-wave emission from Jupiter and interpret the radio astronomical observations of Jupiter. The results of this activity are described in Appendix D, which is a preprint of a paper entitled, "Search for Sulfur (H_2S) on Jupiter at Millimeter Wavelengths" by Joiner et al., (1991).

III. VENUS STUDIES

III.A. Studies of the Millimeter-Wave Spectrum of Venus

III.A.1 Radiative Transfer Modelling of the Atmosphere of Venus

In the previous reports, detailed descriptions regarding the laboratory measurement of the millimeter-wave opacity of constituents of the atmosphere of Venus were presented. In order to study the role of these constituents (and other possible absorbers) on the millimeter-wave emission of Venus, a radiative transfer model has been developed. This model incorporates the results of our measurements in addition to other data that is pertinent to the atmosphere of Venus.

III.A.1.1 Development of the Radiative Transfer Model

In the classic theory of radiative transfer, the radiated energy of a black body (also known as brightness, in units of Joules or ergs) is related to its physical temperature through the Plank function given as,

$$B_\nu (T) = \frac{h\nu^3}{c^2\left[\exp\left(\frac{h\nu}{kT}\right)-1\right]} \tag{11}$$

where c is the speed of light, h is Plank's constant (6.63x10-34 J s) and k is Boltzman constant (1.38x10-23 J/k). In general, the disk average brightness can be expressed as per Liou (1980),

$$B_\nu(T_D) = 2\int_0^1 B_\nu(T_s)\, e^{-\tau_1/\mu}\ \mu d\mu + 2\int_0^1\int_0^{\tau_1} B_\nu\,[T(\tau')]e^{-\tau'/\mu}d\tau' d\mu \qquad \textbf{(12)}$$

where the first term is the brightness of the surface observed at the top of the atmosphere reduced by the absorption of the intervening layers by a factor $e^{-\tau_1/\mu}$. The second term of this expression indicates the brightness emanating from within the atmosphere of Venus. The quantity μ is defined as the cosine of the angle between the vertical and the emission angle of the planet as shown in Figure 1 . Thus the integration over μ results in the average brightness of the entire planet. The quantity τ is known as the optical depth and is defined as,

$$\tau_\nu(Z) = \int_0^Z \alpha_\nu(Z')\, dZ' \qquad \textbf{(13)}$$

where Z is the depth as measured from the top of the atmosphere, and $\alpha_\nu(Z)$ is the total absorption coefficient of all the absorbing constituents at depth Z (τ_1 is the optical depth at the planet's surface). For a simple spherical planet, the integration may be simplified to a single exponential integral (Goodman, 1969) so that,

$$B_\nu(T_D) = 2B_\nu(T_S)\,E_3(\tau_1) - 2\int_0^{\tau_1} B_\nu(T(\tau'))\, dE_3(\tau') \qquad \textbf{(14)}$$

where,

$$E_n(\tau) = \int_1^\infty \frac{1}{y^n} e^{-\tau y} dy \qquad \textbf{(15)}$$

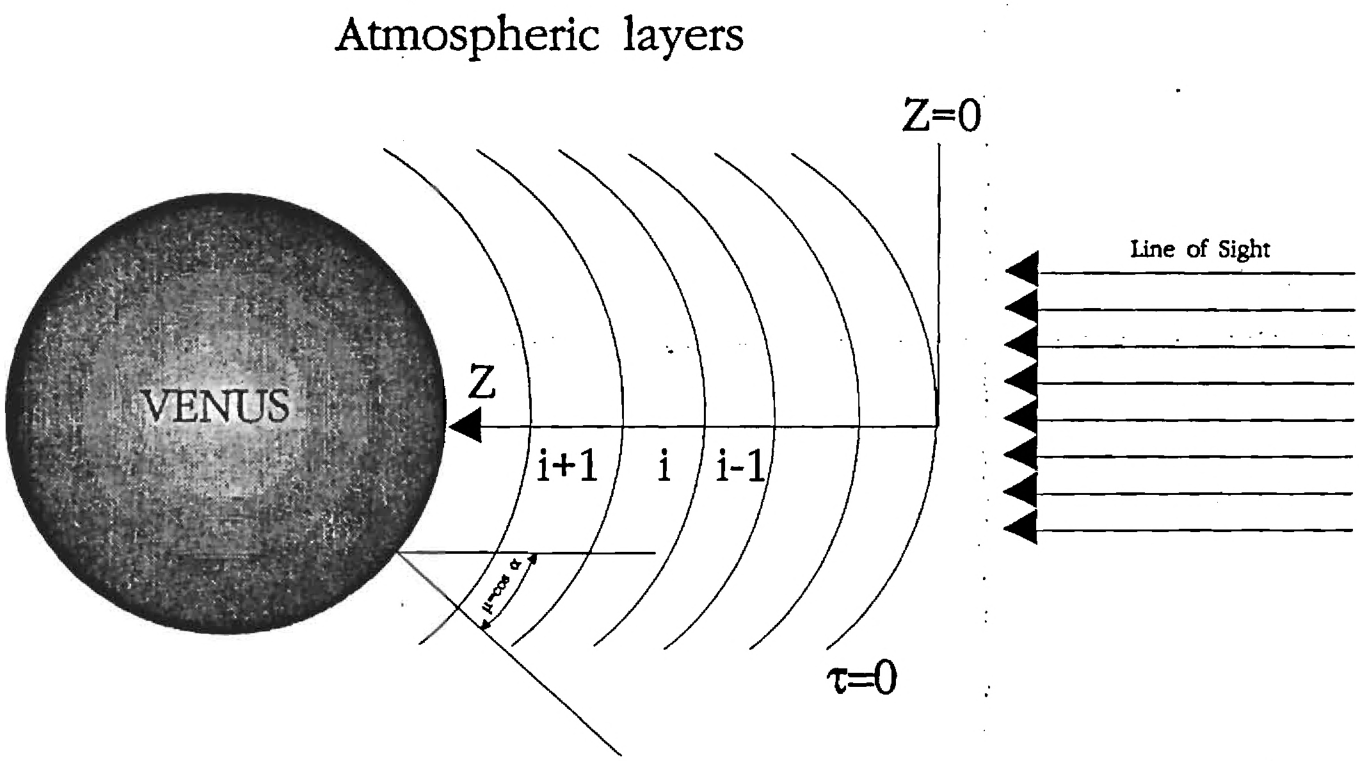

Figure 1 Sketch of the geometry of the planet Venus.

and $y=1/\mu$.

Numerical implementation of the radiative transfer model have been achieved where the integral in equation (14) is evaluated dividing the atmosphere into discrete layers as shown in Figure 1. The average pressure, temperature, and altitude at each discrete layer are determined using the pressure-temperature profile described by Seiff et al. (1980). The integration is evaluated starting at the top of the atmosphere (Z=0) and is terminated at the surface of the planet. The brightness at each layer i is evaluated in addition to the corresponding optical depth of that particular layer i. The contributions from each layer are then added to yield the total brightness and hence the disk-averaged brightness temperature of the planet.

Another quantity that is useful when studying the effects of the atmospheric constituents of Venus on its emission is the weighting function W. This function describes the location within the atmosphere from which most of contribution to the total brightness is occurring. In the developed model, the weighting function at a particular frequency ν is defined as,

$$W_\nu(Z) = dE_3(\tau(Z)) \quad . \tag{16}$$

a. **Contributors to the Radiative Transfer Model**

To fully implement a radiative transfer model, several variables must be included in the model. Such variables include the pressure-temperature profile of the atmosphere of the planet, the expected opacities of the major atmospheric constituents, and the distribution of these absorbing constituents within the atmosphere.

b. Pressure-Temperature Profile of Venus

Several pressure-temperature profiles of Venus have been developed using data from entry probes released in the atmosphere of Venus in the late seventies. Seiff et al. (1980) developed such profiles using the collected data from the four Pioneer-Venus entry probes. In our model, the profile obtained from the sounder probe (released over the equator of Venus) is employed. In addition, a standard disk radius of 6120 km is used for Venus (this disk radius includes the physical radius of the planet in addition to the height of the atmosphere)

c.. Gaseous CO_2 Absorption

Gaseous carbon dioxide (CO_2) is considered to be the major absorber in the atmosphere of Venus. The absorption of CO_2 can be attributed to the collisions of CO_2 molecules in the atmosphere of Venus. Ho et al. (1966), determined the following expression for the absorptivity, α, of a mixture of CO_2 and N_2 under high pressure ($p > 5$ atm);

$$\alpha = 1.15x10^{8}\left[q_{CO_2}^2 + .25 q_{CO_2} q_{N_2} + .0054 q_{N_2}^2\right] f^2 p^2 T^{-5} \qquad dB/km \qquad \mathbf{(17)}$$

where p is the pressure in atmosphere, T is the temperature in K, f is the frequency in GHz, and q is the number mixing ratio. For the atmosphere of Venus, CO_2 composes about 95% of the atmosphere while N_2 corresponds to about 3.0 % . In the development of the radiative transfer model, the above expression is used to compute the opacity of gaseous CO_2 in the atmosphere of Venus.

d. **SO_2-CO_2 Absorption**

The results of the measured opacity of gaseous SO_2 in a CO_2 atmosphere indicate that the Van-Vleck Weisskopf formalism can be used to determine the opacity of sulfur dioxide for Venus-like conditions at wavelengths shortward of 1.5 cm. This key finding differs from previous results of Steffes and Eshleman (1981) and Jansen and Poynter (1981) which suggested that microwave SO_2 opacity had an f^2 dependence. As a result of our new finding, a new upper limit on the abundance of gaseous SO_2 can be determined.

In order to calculate limits on the SO_2 abundance in the atmosphere of Venus, a uniform SO_2 mixing ratio at altitudes below 48 km and an exponential depletion above the cloud base (48 km) is assumed. Based on this assumption and the findings regarding the opacity of SO_2, the radiative transfer model is then used to compute the expected brightness temperature of Venus considering only the effects of CO_2 and SO_2 at 1.35 cm. The Venus brightness at this wavelength has been measured by several observers, and most recently by Steffes et al. (1990). In addition, the effects of the other absorbers at 1.35 cm on the total opacity of the atmosphere of Venus are minimal (especially gaseous sulfuric acid). Thus an accurate estimate of the abundance of gaseous SO_2 based on the microwave absorption of Venus at 1.35 cm can be made. Our model shows that a uniform mixing ratio of 62 ppm (+183,-62) at altitudes below 48 km gives a brightness temperature that is equivalent to the measured brightness temperature of Venus at 1.35 cm.

As for the contribution of gaseous SO_2 to the millimeter-wave emission of Venus, the results from the radiative transfer model indicate that SO_2 does indeed have an effect on the brightness temperature of Venus. A decrease in brightness temperature of 5 K (from the brightness temperature based only on CO_2) is observed at 95 GHz for a mixing ratio of 62 ppm for altitudes below 48 km . This decrease is quite comparable with the effects of other absorbers in the atmosphere of Venus as indicated in Table I.

Figure 2 shows the weighting function at 95 GHz based only on CO_2 and SO_2 opacities. An examination of this figure reveals that most of the contribution to the brightness temperature is originating between the 42.5 and 50 km altitudes.

e. **Liquid Sulfuric Acid Condensates**

Preliminary results from the radiative transfer model indicate that liquid H_2SO_4 does indeed affect the brightness temperature of Venus at 95 GHz. A decrease in brightness temperature of 2 K is obtained (see Table I) for a uniform cloud layer in the 48-50 km altitude range. This decrease in brightness temperature is comparable with that attributable to gaseous SO_2 (SO_2 is assumed to be uniformly mixed below 48 km altitude and exponentially decreasing above). However, this variation in brightness

Frequency (GHz)	Computed Brightness Temperature (k)	Constituents Present	Abundance
95.0	362.0	CO_2	95 %
95.0	357.1	CO_2, SO_2	62 ppm (Alt.< 48.0 km, 0 above 48 km.)
95.0	357.0	CO_2,SO_2,H_2O	70 ppm (decrease linearly below and above 30 km.
95.0	355.2	CO_2,SO_2,H_2O Liquid H_2SO_4	50 mg/m^3 (48-50 Km.)

Table I Effect of the absorbing constituents of Venus on the calculated brightness temperature at 95 GHz.

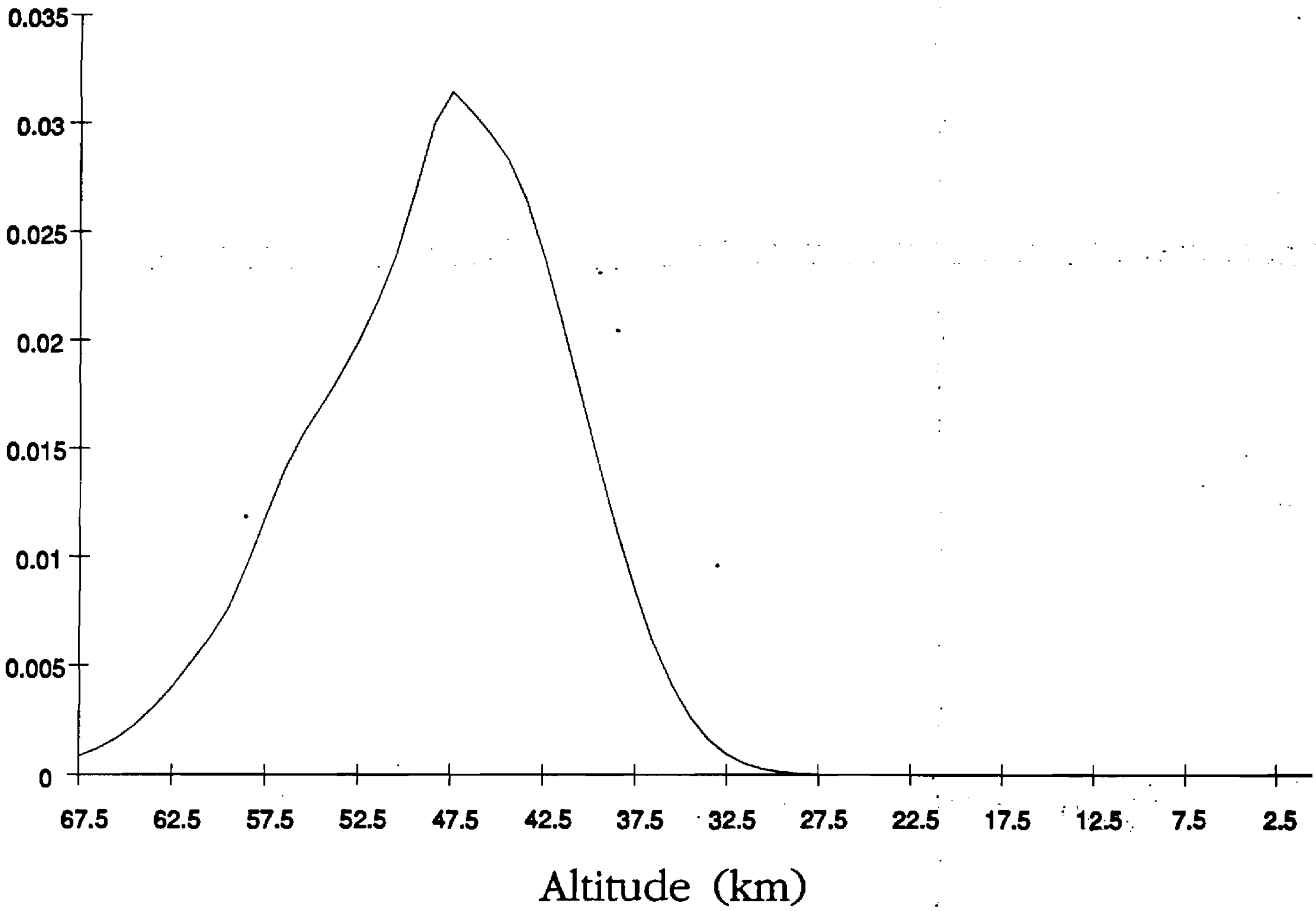

Figure 2: Weighting function of SO_2 at 95 GHz.

temperature is much less than the observed variation in the millimeter-wave emission of Venus. Recently, de Pater (1991) reported observing a variation of 30 K in the brightness temperature of Venus at 112 GHz. This large discrepancy may be attributed to the fact that the calculation from the radiative transfer model does not include the contributions from gaseous sulfuric acid which is considered to be one of the major absorbers at millimeter-wavelengths. In addition, this decrease may be due to the scattering effect of the cloud condensates which tend to lower the actual brightness temperature of Venus at this particular frequency.

The resulting weighting function at 95 GHz considering CO_2, SO_2/CO_2 , and liquid sulfuric acid condensates is shown in Figure 3. An examination of this figure shows an abrupt change in the weighting function is observed as a result of the presence of the liquid sulfuric acid cloud between 48 and 50 km.

f. **Scattering effects of the cloud condensates**

Another possible effect that can influence the measured variations in the emission of Venus may be attributed to backscattering by the cloud condensate. This backscattering effect can cause a cooler brightness temperature of Venus resulting from the reflection of the cooler atmosphere above the main cloud layer. In order to investigate this phenomena, our radiative transfer model will be modified to include the effect of backscattering by cloud condensates. As a result, we can then infer the effects, if

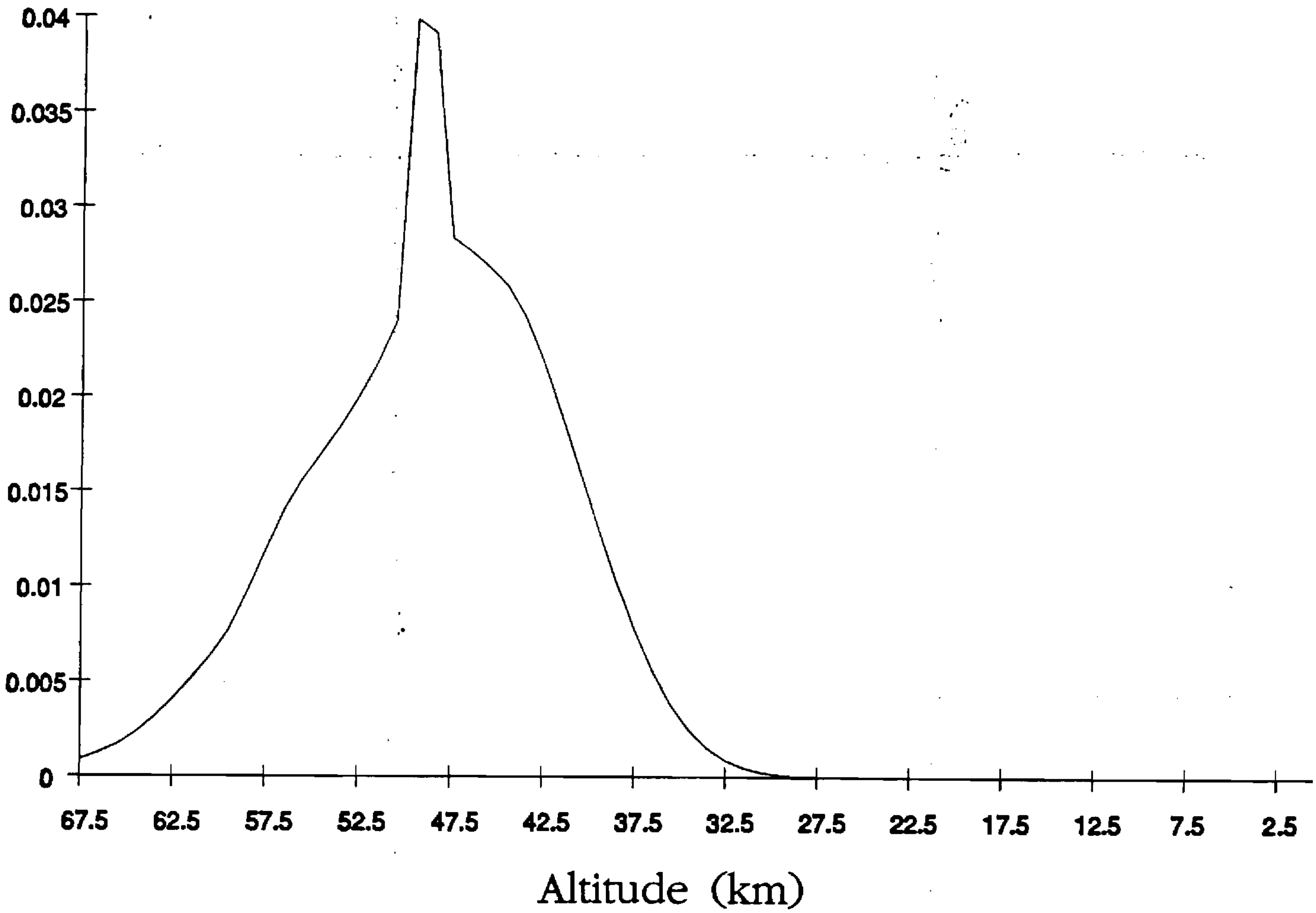

Figure 3: Weighting function as a result of the liquid sulfuric acid condensates in the clouds of Venus at 95 GHz.

any, of the cloud scattering on the expected emission of Venus at millimeter-wavelengths.

g.. H_2O Vapor

Although water vapor is known to exist in the atmosphere of Venus, discrepancies regarding its abundance are still unresolved. Some estimate that the H_2O concentration is on the order of several thousands ppm as a result of the Pioneer-Venus gas chromatography (PVGC) experiment (Oyama,1979), whereas other measurements of H_2O vapor range from 20 to 200 ppm. Recently, Lewis and Gripper (1990) concluded that a mean water abundance of 50 $\pm$20 ppm and a near-surface water vapor abundance of 10 $\pm$4 ppm provide a conservative estimate of the water vapor abundance in the atmosphere of Venus.

In order to include the effects of H_2O vapor in the development of the radiative transfer model, a knowledge of the opacity of water vapor in a CO_2 atmosphere is needed. For this, the results reported by Waters (1976) are used (with the modification of the broadening parameter to account for CO_2 broadening) to infer the opacity of water vapor for frequencies below 300 GHz.

The results of incorporating the water vapor opacity in the radiative transfer model indicate that H_2O does not affect the brightness temperature at 95 GHz (see Table I). In this case, a drop of only 0.1 K is observed when the opacity of water is added to the atmospheric opacity of Venus (water vapor abundance of 70 ppm is assumed at 30 km with linear decrease in abundance for altitudes above and below 30 km).

III.A.2 NEW LABORATORY MEASUREMENTS:

Laboratory Measurement of the Opacity of Gaseous Sulfuric Acid at Millimeter-Wavelengths

As discussed in the previous sections, a complete understanding of the millimeter-wavelength emission from Venus requires an accurate determination of the opacities of the major absorbers in the Venus atmosphere. Among these absorbers, gaseous H_2SO_4 is considered to be one of the primary absorbers at millimeter-wavelengths, and the knowledge of its opacity is crucial in any modelling of the emission of Venus.

Unfortunately, little (if any) laboratory work has been performed to measure the opacity of gaseous H_2SO_4 at millimeter-wavelengths for Venus-like conditions. In addition, the simple extrapolation of the microwave data of Steffes (1985,1986) to higher frequencies is not straightforward and it could lead to erroneous results. Janssen (private communication, 1987) developed a theoretical model for the absorption coefficient based on 11892 absorption lines extending into the submillimeter region. As a result, we estimate the opacity of H_2SO_4 in a CO_2 atmosphere at 95 GHz to be on the order of .12 dB/km-ppm (T=590 K ,P= 2 atm). This estimate can then be used as a basis to develop a laboratory experiment to measure the opacity of H_2SO_4.

According to our measured partial pressure of H_2SO_4, a mixing ratio of 12500 ppm (by volume) can be expected at 590 K when mixed with 2 atm of CO_2. This results in an absorption coefficient on the

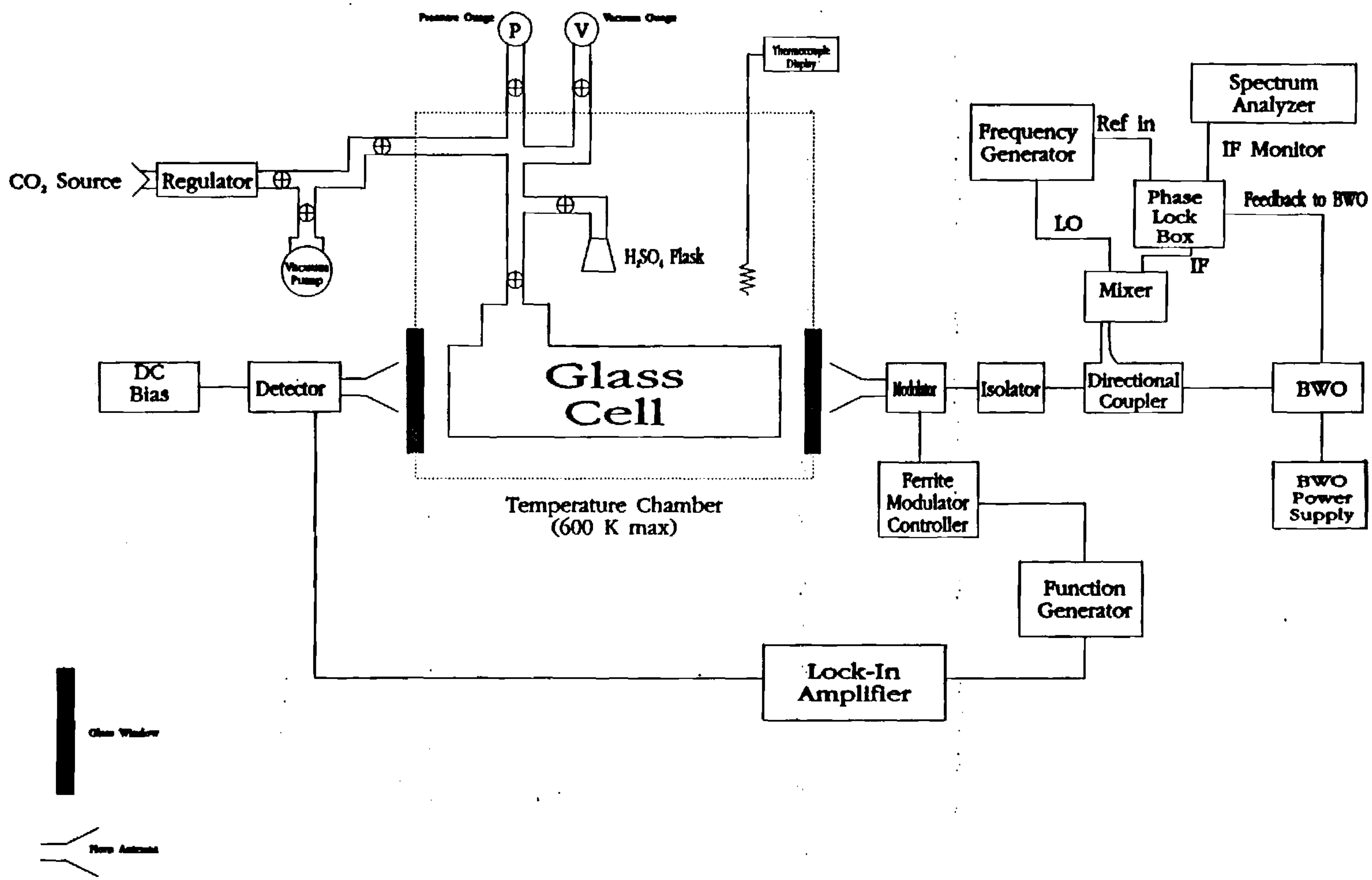

Figure 4: Schematic diagram of the experimental setup used to measure the opacity of gaseous sulfuric acid at 95 GHz.

order of 1500 dB/km (1.5 dB/m). Hence, the absorption coefficient can be measured using a free space transmission setup with a transmission cell of length 1 m. The proposed setup of this experiment is shown in Figure 4.

III.A.2.1 **Experimental Configuration and Procedure**

The experimental layout shown in Figure 4 includes a free space transmission cell in addition to a CW phase-locked BWO in order to insure that the output variation of the source is kept to a minimum. The output of the BWO is fed into a horn antenna which transmits the millimetric wave through the glass cell. The outgoing wave is received by the second antenna where the signal is detected by a W-band detector.

In order to reduce the amount of interference between the propagating wave and the cell wall, the radius of the cell must be chosen greater than the radius of the first Fresnel zone (the Fresnel zone is defined as that volume surrounding a ray path through which another ray can travel and arrive at the receiver having travelled no more than .5 wavelength farther than the primary ray; Bullington, 1957). Thus,

$$R_c \succ \left[\frac{\lambda r}{2}\right]^{1/2} , \qquad \textbf{(18)}$$

where R_c is the radius of the cell, and λ is the wavelength (in this case 3 mm), and r is the separation distance between the two horns (1 m). Using equation (18), a minimum cell radius of 1.52" is required. In the proposed experimental setup, we employ a glass cell with a radius of 2.5".

The measurement will be performed at temperatures between 550 and 600 K so as to provide sufficient H_2SO_4 vapor in the glass cell. Gaseous CO_2 is then introduced in the cell in order to raise the total pressure to 2 atm (This value represents a safe upper limit for internal pressure of the glass cell). The resulting absorption due to the gas mixture can then be measured and the process is repeated for additional lower pressures.

III.A.2.2 **Incorporation of the Results into the Radiative Transfer Model**

The results of the measurement of the opacity of gaseous sulfuric acid in addition to the results of our already completed laboratory measurements will be incorporated into the radiative transfer model to compute the effect of these constituents on the emission of Venus. In addition, our model will be used to study the effects of other possible absorbers. This will require additional enhancements on the already working model. The results of this new data will provide much essential information needed to explain the observed variations in the emission of Venus at millimeter-wavelengths, and infer the constituent variations responsible for the emission fluctuations.

III.B. Radio Occultation Studies of the Venus Atmosphere with the Magellan Spacecraft

Soon after the launch of the Magellan spacecraft (in 1989), it was suggested by P. Steffes of Georgia Tech, that Magellan could be used for radio occultation studies of the Venus atmosphere. Because of its larger antenna, the stronger transmitted signal could be tracked deeper into the Venus atmosphere, and the inferred quantities, such as the 13 cm absorptivity due to gaseous sulfuric acid could be determined to a much higher accuracy. This is discussed in a letter to the Magellan Program dated 27 November 1989, attached as Appendix A.

On 7 May 1991, we made a presentation at the Magellan Atmospheric Science and Contingency Workshop, and subsequently made the same presentation to the Magellan Project Steering Group, detailing the goals and required support for this experiment (see Appendix B). The experiment was approved, and will be conducted during three successive orbits on October 5, 1991. The operational aspects of the experiment are highlighted in Appendix C. We are currently assisting the Magellan Project in designing the spacecraft maneuver required for this experiment. In the next grant year, we will have access to the data in order to process it for the atmosphere parameters, particularly the microwave absorptivity, which is related to the abundance of gaseous H_2SO_4.

IV. PUBLICATIONS AND INTERACTION WITH OTHER INVESTIGATORS

After attending the October, 1990, AAS/DPS meeting (Charlottesville, VA) where we presented 4 papers (Fahd and Steffes, 1990a; Fahd and Steffes, 1990b; Joiner and Steffes, 1990; Jenkins and Steffes, 1990; reprints were included with Semiannual Status Report #15) we prepared and submitted two papers to the new Journal of Geophysical Research: Planets. These papers have been accepted for a special issue on Laboratory Research for Planetary Atmospheres. The first is entitled "Modeling of the Millimeter-Wave Emission of Jupiter Utilizing Laboratory Measurements of Ammonia (NH_3) Opacity" by Joiner and Steffes. The second is entitled "Laboratory Measurement of the Millimeter-Wave Properties of Liquid Sulfuric Acid (H_2SO_4)" by Fahd and Steffes. Preprints of thes papers were included with Semiannual Status Report #15 for this grant. We have also submitted a paper to the IEEE Transactions on Microwave Theory and Techniques entitled "Search for Sulfur (H_2S) on Jupiter at Millimeter Wavelengths," by Joiner and Steffes (1991b) describing our observations of Jupiter at 1.4 mm, and the accompanying laboratory measurements of H_2S at that wavelength. A preprint of this paper is attached as Appendix D, and it will be published in a special issue on "Microwaves in Space," commemorating the International Space Year.

A large source of interaction with other planetary researchers has been our recent initiative to involve the Magellan Project in atmospheric studies. As a result, we have worked with members of the Magellan Project Steering Group (PSG) in order to justify and plan a radio occultation measurement of the Venus atmosphere. These have included (from JPL) Thomas W. Thompson (Science Manager), James Scott (Project Manager), Richard Austin, and Dan Lyons. From NASA

Headquarters we have worked with David Okerson, and from the Mission Science Team we have worked closely with G. Leonard Tyler from Stanford University and Gordon H. Pettengill from M.I.T.

Our work has been complemented by our past involvement in the Pioneer-Venus Guest Investigator Program in which we processed radio occultation data in order to obtain 13 cm absorptivity profiles for the Venus atmosphere (Jenkins and Steffes, 1991). This has kept us in close contact with a large number of Venus investigators. More informal contacts have been maintained with groups at the California Institute of Technology, with the Stanford Center for Radar Astronomy (Drs. V.R. Eshleman and G.L. Tyler, regarding Voyager and Magellan results , and with JPL (Drs. Tom Spilker, Samuel Gulkis, and Michael Klein, regarding both laboratory measurements and radio astronomical observations of the outer planets and Venus). We have also worked with Dr. Imke de Pater (University of California-Berkeley) by using our laboratory measurements of atmospheric gases in the interpretation of radio astronomical observation of Venus and the outer planets. We have also studied possible effects of the microwave opacity of cloud layers in the outer planets' atmospheres. In this area, we have worked both with Dr. de Pater and with Dr. Paul Romani (Goddard SFC).

In the beginning of the next grant year, we will again present results of our latest work at the annual AAS/DPS meeting. We will also complete and submit a paper to Icarus describing our laboratory measurements of the microwave and millimeter-wave opacity of SO_2, and how the results affect interpretation of the microwave and millimeter-wave emission from Venus. We expect to be far enough along on processing our millimeter-wave laboratory data from H_2SO_4 and data from the Magellan Radio Occultation Experiment so as to present results both at the October 1992 AAS/DPS meeting and in journals.

V. PROPOSED PROCEDURE AND LEVEL OF EFFORT

Over this past grant year we have continued a very active program of laboratory measurements of the microwave and millimeter-wave properties of planetary atmospheric constituents. We have also been involved in observational and interpretive studies of the microwave and millimeter-wave absorption and emission from planetary atmospheres. In the next grant year, we intend to complete the analysis of our observations of the 1.4 mm emission spectrum of Jupiter. We will also conduct laboratory measurements of the millimeter-wave opacity from gaseous H_2SO_4 under simulated Venus conditions. This is an especially difficult task given the high temperatures required to obtain enough H_2SO_4 vapor so as to be able to measure its opacity, and the high pressures characteristic of the Venus atmosphere. Once these measurements are completed, it will be possible to develop a millimeter-wave radiative transfer model for Venus which should be able to account for the spatial variations in the emission at millimeter wavelengths. Likewise, we will begin analysis of the radio occultation data obtained from the Magellan Spacecraft.

Finally, we intend to pursue an integrated multi-spectral analysis of Venus atmospheric data employing: 1) recent Pioneer-Venus radio occultation data for 13 cm opacity in the Venus atmosphere (ref. Jenkins and Steffes, 1991); 2) recent earth-based observations of the microwave (ref. Steffes et al., 1990) and millimeter-wave (ref. de Pater et al., 1991) emission from Venus, and 3) recent

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REPORT

TO THE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

SEMIANNUAL STATUS REPORT #17

for

GRANT NAGW-533

LABORATORY EVALUATION AND APPLICATION OF

MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED

CONDITIONS FOR PLANETARY ATMOSPHERES

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November 1, 1991 through April 30, 1992

Submitted by

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I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing atmospheric constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or using laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. For example, laboratory measurements performed by Fahd and Steffes (1992), under Grant NAGW-533, have shown that the opacity from gaseous SO_2 under simulated Venus conditions can be well described by the Van Vleck-Weisskopf lineshape at wavelengths shortward of 2 cm, but that the opacity of wavelengths greater than 2 cm is best described by a different lineshape that was previously used in theoretical predictions. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements <u>and</u> to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identify and abundance profiles of constituents in those planetary atmospheres.

A. Laboratory Measurements

An important source of information regarding the Venus atmosphere is the increasing number of high spatial resolution millimeter-wavelength emission measurements which have been recently conducted. (See, for example, de Pater et al., 1991). Correlative studies of these measurements with Pioneer-Venus radio occultation measurements (Jenkins and Steffes, 1991), with newly conducted Magellan radio occultation experiments (Steffes et al., 1991), and with our longer wavelength emission measurements (Steffes et al., 1990), will provide new ways for characterizing temporal and spatial variations in the abundance of both gaseous H_2SO_4 and SO_2, and for modeling their roles in the subcloud atmosphere. However, unambiguous results require that we have dependable knowledge of the microwave and millimeter-wave opacity of gaseous and liquid H_2SO_4, and of gaseous SO_2 under Venus conditions.

While some laboratory measurements of the microwave absorption properties of gaseous SO_2 under simulated Venus conditions were made at 13 cm and 3.6 cm wavelengths by Steffes and Eshleman (1981), no measurements have been made at shorter wavelengths. As a result, we conducted laboratory measurements of the 13 cm, 1.35 cm, and 3.2 mm opacity of gaseous SO_2. These measurements and their applications have been described in a paper by Fahd and Steffes (1992). Likewise, we recently completed laboratory measurements of the millimeter-wave dielectric properties of liquid H_2SO_4 in order to model the effects of the opacity of the clouds of Venus on its millimeter-wave emission spectrum (Fahd and Steffes, 1991a). The final experiment needed for proper interpretation of the

Venus millimeter-wavelength continuum is laboratory measurement of the opacity of gaseous H_2SO_4. We have recently completed such measurements. (See Section II of this report). In the remainder of the current grant year (ending October 31, 1992) we will complete development of a formalism for computing the millimeter-wave opacity of gaseous H_2SO_4, and apply it to our millimeter-wavelength radiative transfer model for Venus, which is described in Fahd and Steffes (1992). Already this work has shown that there are specific millimeter-wave frequencies which are especially sensitive to the abundance of H_2SO_4 vapor in the lower Venus atmosphere.

B. Magellan/Venus Radio Occultation Experiment

We have also been successful in this grant year in conducting a radio occultation experiment with the Magellan Spacecraft (see Steffes et al., 1991). This is the first atmospheric work conducted with Magellan and the atmosphere was probed to deeper levels than was possible with the less powerful Pioneer-Venus Orbiter radio transmission system. This experiment was conducted on October 5, 1991, and consisted of three entry occultation experiments. A description of this experiment is included in Section III of this report. This successful demonstration has shown the feasibility of using the Magellan spacecraft to provide highly accurate atmospheric refractivity and absorptivity profiles, which in turn, can be used to determine profiles of temperature, pressure, and gaseous H_2SO_4 abundance in the Venus atmosphere. We intend to use future Magellan radio occultation data as part of an integrated multi-spectral analysis of Venus atmospheric data.

II-MEASUREMENT OF THE OPACITY OF GASEOUS SULFURIC ACID (H_2SO_4) AT W-BAND (94.1GHZ)

A-Motivation

As discussed in previous reports, a complete understanding of the millimeter-wavelength emission from Venus requires an accurate determination of the opacities of the major absorbers in the Venus atmosphere. Recent observations of the millimeter-wave emission from Venus at 112 GHz (2.6 mm) have shown significant variations in the continuum flux emission (de Pater et al., 1991) which may be attributed to the variability in the abundances of absorbing constituents in the Venus atmosphere. Such constituents include gaseous H_2SO_4, SO_2, and liquid sulfuric acid (cloud condensates). Recently, Fahd and Steffes (1991a) have shown that the effects of liquid H_2SO_4 and gaseous SO_2 cannot completely account for this measured variability in the millimeter-wave emission of Venus. To fully understand potential sources of this variation, one needs to study the effects of gaseous sulfuric acid on the millimeter-wave emission of Venus.

Unfortunately, little (if any) laboratory work has been performed to measure the opacity of gaseous H_2SO_4 at millimeter-wavelengths for Venus-like conditions. In addition, the simple extrapolation of the microwave opacity of H_2SO_4 measured by Steffes (1985,1986) to higher frequencies is not straightforward and could lead to erroneous results.

To investigate the role of gaseous H_2SO_4 in the atmosphere of Venus, we have measured the opacity of gaseous H_2SO_4 in a CO_2

atmosphere at 550, 570, and 590 K from 1 to 2 atmospheres total pressure at 94.1 GHz. This work represents the first time that a measurement of the millimeter-wave opacity of a H_2SO_4/CO_2 gaseous mixture has been conducted for Venus-like conditions. We have also developed a modeling formalism to calculate the expected opacity of this gaseous mixture at other frequencies based on our measured results and the results reported by Steffes (1985,1986). Comparisons between the measured and the theoretically derived opacities of H_2SO_4/CO_2 mixture are also presented.

B-Laboratory Configuration

The experimental system used to measure the millimeter-wave opacity of gaseous H_2SO_4 in a CO_2 atmosphere consists of two major subsystems: The planetary atmospheric simulator and the millimeter-wave subsystem as diagrammed in Figure 1.

The planetary atmospheric simulator subsystem consists of a glass cell (which contains the gaseous mixture), two pressure gauges, a thermocouple display unit, a CO_2 tank and an oil diffusion vacuum pump. In this subsystem, the glass cell (length=27") is placed into a temperature controlled oven with a maximum temperature of 600 K. The temperature of the oven is electronically controlled, with a temperature variation of less than ± 5 K. A calibrated thermocouple unit is inserted into the glass cell in order to display the system's temperature. Liquid sulfuric acid is deposited into a custom made flask prior to the start of the measurements. The pressure and vacuum status of the planetary atmospheric subsystem are monitored via two gauges. Gauge

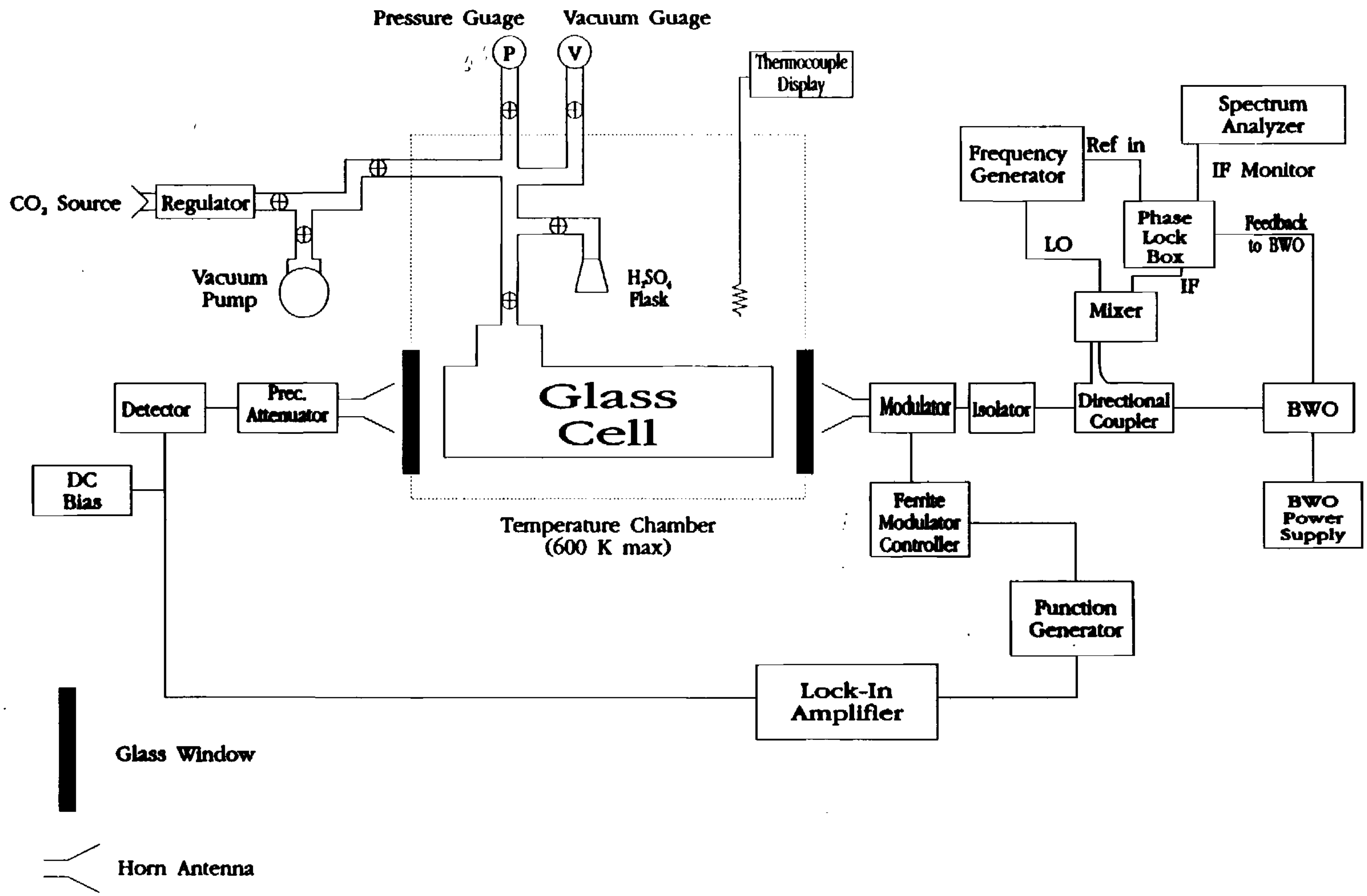

Figure 1 Block diagram of the atmospheric simulator as configured for measurements of the millimeter-wave absorption of gaseous H_2SO_4 under Venus atmospheric conditions at 94.1 GHz.

P (0-80 psig) with a display resolution of 1 psig and an accuracy of ± 3 psig is used to measure the internal pressure of the glass cell resulting from the introduction of the H_2SO_4/CO_2 gaseous mixture into the system. Gauge V is a thermocouple vacuum gauge that is able to measure pressures between 0-800 Torr with 1 Torr display resolution and an accuracy of 1% of full scale. It is used to monitor the vacuum status of the glass cell. Two Pyrex-66 glass windows are installed on the two sides of the oven to allow the propagation of the electromagnetic energy. A network of 3/8" stainless-steel tubing and valves connect the components of the planetary atmospheric subsystem so that each component may be isolated from the system as necessary. An oil diffusion pump is used to evacuate the glass cell prior to the introduction of the gaseous mixture.

The millimeter-wave subsystem (also shown in Figure 1) consists of a Siemens backward wave oscillator (BWO) powered by a MicroNow power supply. The BWO is electrically isolated from the waveguide apparatus by use of a polyester sheet and nylon screws on the waveguide flange of the BWO. (this is necessary to insure phase locking stability). Enroute to the glass cell, the signal is first sampled by a 10dB directional coupler. The sampled signal passes into a harmonic mixer as part of the phase locking system. The majority of the signal goes on through an isolator, which prevents reflections to the BWO, and is then electronically chopped by a ferrite modulator before entering the cell. The received power is detected by a schottky barrier point contact diode detector at 94 GHz. Power changes are measured as voltage changes at the detector. In order to give the detector the most linear response, the diode is biased with a current of 10 mA. The detector's output is measured with a lock-in amplifier where the modulation reference comes from a function generator which drives the ferrite switch. The modulation frequency is 100 Hz. The output of the lock-in amplifier is fed into a digital voltmeter.

Phase locking stabilizes the frequency output of the BWO. The -10dB port of the directional coupler feeds the BWO output into the harmonic mixer where it is heterodyned with the local oscillator (LO). A synthesized signal generator (2-18 GHz) serves as the LO and as the reference signal for the phase- locked loop. The intermediate frequency (IF) from the mixer is fed into the phase detector. The phase-locked loop functions only when the LO harmonic is below the BWO frequency, i.e., setting the LO to 9.368 GHz gives 9.368 GHz x 10= 93.680 GHz + 420 MHz IF = 94.1 GHz. An IF monitor output on the phase detector allows viewing the locked waveform with a spectrum analyzer.

In order to minimize the effect of any reflections from the cell wall, the radius of the cell must be chosen greater than the radius of the first Fresnel zone (the Fresnel zone is defined as that volume surrounding a ray path through which another ray can travel and arrive at the receiver having travelled no more than 1/2 wavelength farther than the primary ray; Bullington, 1957). Thus, it follows that

$$R_c > \left[\frac{\lambda r}{2}\right]^{1/2} \quad , \tag{1}$$

where R_c is the radius of the cell, λ is the wavelength (in this case 3 mm), and r is the separation distance between the two horns (1 m). Using the above equation, a minimum cell radius of 1.52" is required. A glass cell with a radius of 2.5" is used in the experimental setup.

C-Measurement Procedure

The measurement of the millimeter-wave opacity of gaseous H_2SO_4/CO_2 can be summarized as follows: The oven is first heated to the desired temperature. Once the desired temperature is reached, the glass cell is evacuated. By using gauge V as a vacuum monitor, we are able to check the status of the glass cell in order to insure that no major leaks are present. Although the chamber is not leak proof, we are able to maintain a leak rate within the system of less than 1 Torr/hour. The variable attenuator is then set to a predetermined attenuation and the resulting detector voltage is recorded. (The millimeter-wave subsystem is usually turned on for a period of ten hours prior to the beginning of the experiment. This extended time period allows the BWO to warm up and become more stable.) Next, the valve connecting the H_2SO_4 flask and the glass cell is opened allowing the sulfuric acid vapor to equilibrate with the evacuated glass cell. Once equilibrium is reached, the flask's valve is closed and a visual check is made to verify that the remaining liquid acid is clear. Gaseous CO_2 is then introduced in the system at a slow rate so as not to cause any condensation. When the total internal pressure (measured by gauge P) reaches 2 atm, the CO_2 tank is shut off and the two gases are allowed to mix for a specified time period. The attenuation on the variable attenuator is then decreased until the output voltage is equal to the detector voltage of the evacuated glass cell. The opacity of the gaseous mixture can then be inferred from the change in the calibrated attenuator setting. The total internal pressure is then reduced to 1 atm and the measurement process is repeated. This approach has the advantage that the same gas mixture is used for the measurement at various pressures (at each temperature point). Thus, even though some uncertainties may exist due to the mixing ratio of the initial mixture, the mixing ratios at subsequent pressures will be the same, and the uncertainties for any pressure dependence will only be due to the accuracy limits of the absorptivity measurements and not to uncertainties in the mixing ratio.

D-Experimental Uncertainties

In general, the main source of experimental uncertainties in the transmission measurements is the fluctuation in the output power of the source. However, our system is phase locked so as to minimize frequency and output power deviations. Frequency stabilization due to the phase locking system is on the order of ± 20 KHz and power variation is less than ± .02 dB. In order to incorporate the effect of frequency and power fluctuation in our error bars, two measurements are taken for each data point and statistics are developed to compute the 1 σ variation in the measured absorptivity (the number of data points collected was limited due to the availability of some of the equipment).

Additional instrumental uncertainties include uncertainties in the measured pressure and temperature. In the case of pressure measurements, the accuracy was limited by the quality of the two pressure gauges used. The 0-800 Torr gauge has an accuracy of 1% of the full scale while the 0-80 psig gauge has an accuracy of ± 3 psig. The temperature accuracy of the thermocouple used was ± 5 K (temperature uncertainty is shown as horizontal error bars in Figure 2). The accuracy of the variable attenuator is also incorporated in our total uncertainties. The uncertainties due to the mixing ratio have been determined for the three temperatures used in our measurements. Using the expression developed by Spilker (1990) for mixing ratio accuracy, mixing ratios of 1.25% ± 0.13% ,0.87% ± 0.087% and 0.59% ± 0.06% are obtained at 590, 570, and 550 K respectively (in this calculation the partial pressure of H_2SO_4 is obtained from equation (2)). These mixing ratios uncertainties are also included in the vertical error bars shown in Figure 2.

Additional experimental uncertainties include the detector's noise which was characterized from variations in the measured output voltage. The resulting total uncertainties due to noise and instrumental uncertainties are shown in Figure 2 as ±1 σ variations about the mean.

E-Experimental Results and Theoretical Characterization of H_2SO_4 Absorption

Measurement of the opacity of gaseous H_2SO_4 in a CO_2 atmosphere has been performed at 94.1 GHz and at temperature of 550 K, 570 K, and 590 K. These temperatures were chosen so as to allow enough H_2SO_4 vapor in the glass cell. The experiment was conducted at total pressures of 2 and 1 atm for each temperature. For a specific pressure and temperature, the expected vapor pressure of H_2SO_4 can be computed by,

$$\ln p = 6.65 - \frac{6100}{T} \tag{2}$$

where p is the sulfuric acid vapor pressure (atm) and T is the temperature in K. Using the above expression, a mixing ratio of 1.23%, .87% and .59% occurs respectively at 590, 570 and 550 K.

The measured absorption (dB/km) of H_2SO_4/CO_2 at 94.1 GHz is shown in Figure 2 where it is plotted as a function of temperature for 2 and 1 atm. (note that the reported absorptions are normalized to their respective mixing ratios). Using the measured data, a best fit multiplicative expressions has been developed to predict the absorption of H_2SO_4/CO_2 at 94.1 GHz,

$$\alpha = 2x10^{11} p^{.98} q\, T^{-2.9} \qquad dB/km \tag{3}$$

where q is the H_2SO_4 number mixing ratio, P is the total pressure in atmospheres, and T is the temperature in Kelvins.

Although the developed expression is valid for the conditions at which the measurements were performed (i.e. 94.1 GHz), care must be taken when projecting the absorption of H_2SO_4 at frequencies far from 94.1 GHz. To accurately determine the expected absorptivity at other frequencies, we have used the Van Vleck-Weisskopf (VVW) formalism to calculate the opacity of the H_2SO_4/CO_2 gaseous mixture. In this formalism, the absorptivity due to a single resonant line, at frequency f, can be computed as per Townes and Schawlow (1955),

$$\alpha = \alpha_{max} f^2\ \nu_o^{-2}\ \delta\nu^2 \left[\left((\nu_o - f)^2 + \delta\nu^2 \right)^{-1} + \left((\nu_o + f)^2 + \delta\nu^2 \right)^{-1} \right] \tag{4}$$

where f is the frequency in GHz, ν_o is the resonant line frequency,

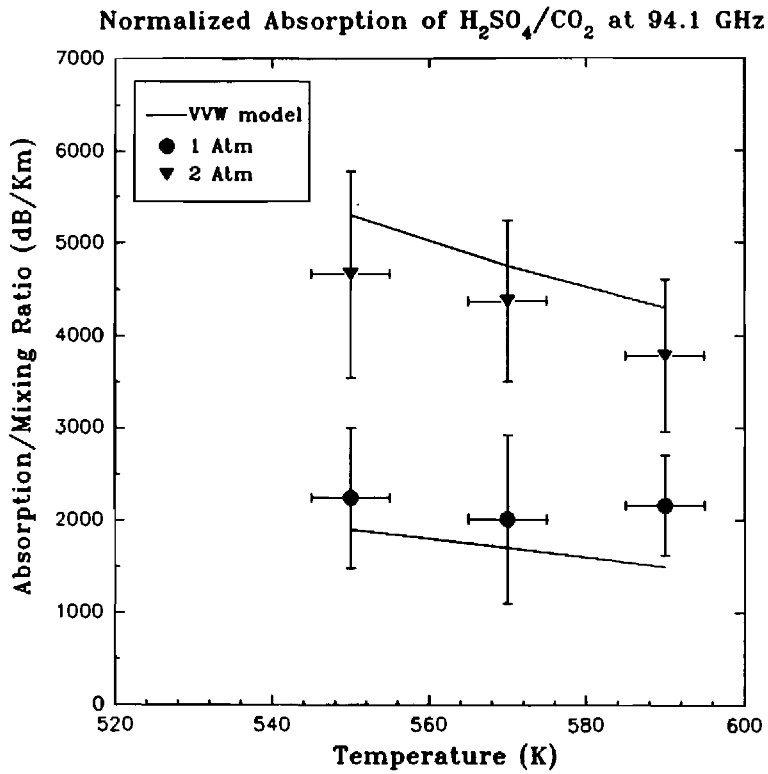

Figure 2 Laboratory measurements of the normalized absorptivity (dB/km) of gaseous H_2SO_4 in a CO_2 Atmosphere at 94.1 GHz. Solid curves are the theoretically calculated absorption from the VVW formalism.

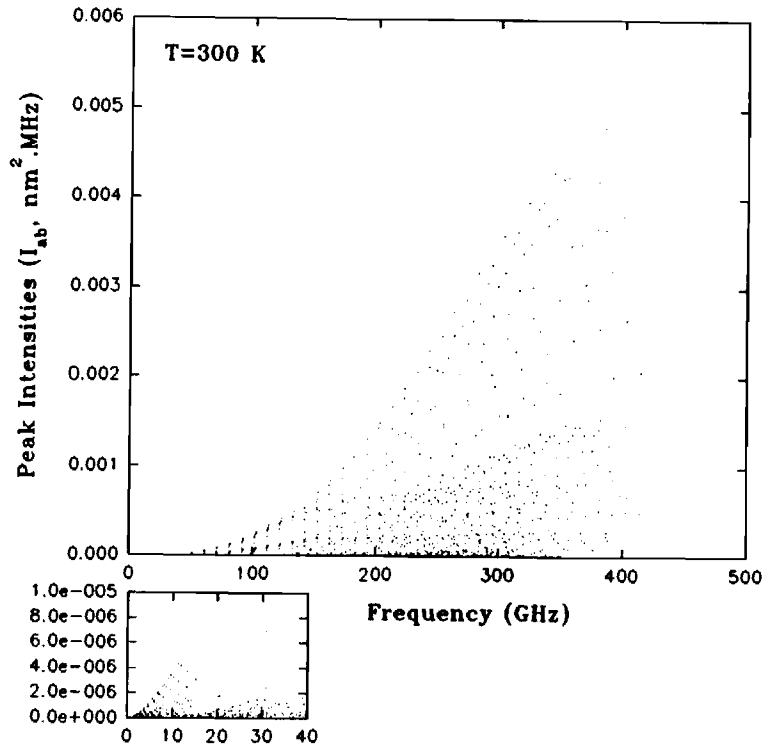

Figure 3 Diagram of the peak intensities at 300 K of the 2359 resonant lines used in the VVW formalism.

and $\delta\nu$ is the line width. In our VVW model, we totaled the contribution from 2359 resonant lines reported by Pickett et al. (private communication, 1991). These lines cover the frequency between 1.5 and 450 GHz. A graphical representation of the resonant lines and their respective line intensities, I_{ab}, are shown in Figure 3 along with an expanded view of the lines between 1.5 and 40 GHz.

In order to fully implement the VVW formalism, an appropriate broadening parameter, $\delta\nu$, must be determined. Previously, Janssen and Poynter (private communication, 1987) used a value of 3 MHz/Torr in their model (their model used a different set of resonant lines) but their results were inconsistent with the measured microwave absorptivity of Steffes (1985,1986). In addition, no measurements of the broadening parameter of H_2SO_4 by CO_2 have been reported. To solve this problem, we adjusted the broadening parameter in the VVW formalism so that the calculated opacity matches the measured absorptivity at 94.1 GHz and the microwave absorption at 2.24 GHz and 8.42 GHz reported by Steffes (1985). As a result, a broadening parameter of 1.55 MHz/Torr was found to fit the above data and seem to provide close agreement between the measured and calculated values of the absorptivity of H_2SO_4 in a CO_2 atmosphere.

A comparison between the calculated and measured opacities of H_2SO_4/CO_2 are shown in Figures 2, 4, and 5 where the discrete data points in Figures 4 and 5 are obtained from Steffes (1985). In Figure 4, the calculated absorption of H_2SO_4/CO_2 mixture at 2.24 GHz and temperatures of 564 and 575 K are compared with the previously

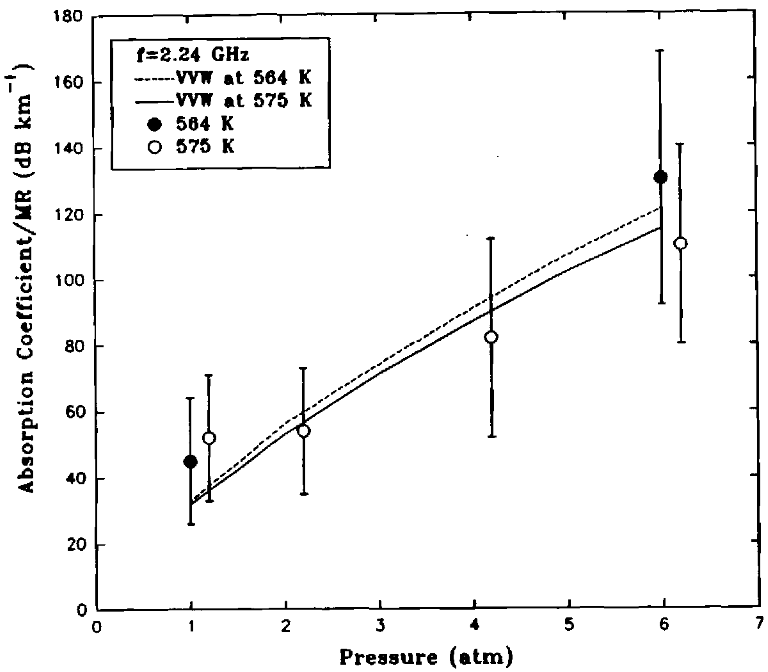

Figure 4 Comparison between the measured absorption (normalized by mixing ratio) of H_2SO_4 (Steffes, 1985,1986) and the calculated absorption from the VVW formalism at 2.24 GHz.

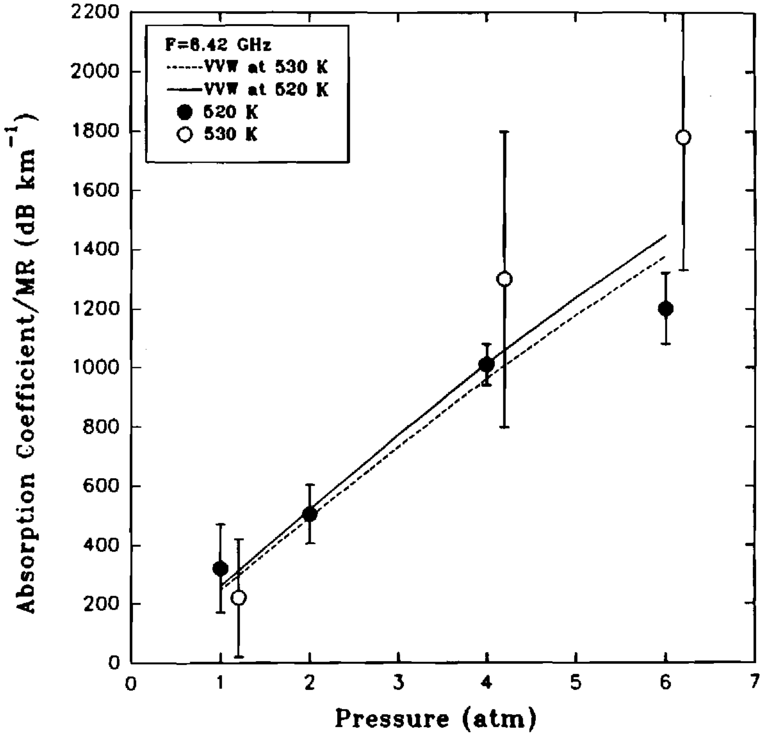

Figure 5 Comparison between the measured absorption (normalized by mixing ratio) of H_2SO_4 (Steffes, 1985,1986) and the calculated absorption from the VVW formalism at 8.42 GHz.

published work. Similarly, Figure 5 shows the results at 8.42 GHz and temperatures of 550 and 520 K. A careful examination of these results indicates that the calculated opacities of H_2SO_4 using the VVW formalism with a broadening parameter of 1.55 MHz/Torr agree well with the measured microwave and millimeter-wave opacities of the gaseous mixture. This finding is quite important since it demonstrates for the first time that the VVW formalism can be used to accurately predict the opacity of H_2SO_4/CO_2 gas mixture over a wide frequency range. As a result, we can use the developed model to predict the opacity of H_2SO_4 at other specified conditions and in particular, we can employ the VVW formalism in our radiative transfer model to study the effects of this gaseous mixture on the emission from Venus.

III. RADIO OCCULTATION STUDIES OF THE VENUS ATMOSPHERE WITH THE MAGELLAN SPACECRAFT

Soon after the launch of the Magellan spacecraft (in 1989), it was suggested by P. Steffes of Georgia Tech, that Magellan could be used for radio occultation studies of the Venus atmosphere. Because of its larger antenna, the stronger transmitted signal could be tracked deeper into the Venus atmosphere, and the inferred quantities, such as the 13 cm and 3.6 cm absorptivity due to gaseous sulfuric acid could be determined to a much higher accuracy.

On May 7, 1991, we made a presentation at the Magellan Atmospheric Science and Contingency Workshop, and subsequently made the same presentation to the Magellan Project Steering Group, detailing the goals and required support for this experiment. The experiment was approved, and was conducted during three successive orbits on October 5, 1991. While data processing is not yet complete, the operational aspects of the experiment are highlighted in Appendix I, which was a poster paper presented at the 1991 AAS/DPS meeting (Steffes et al., 1992). This paper also describes the spacecraft maneuver required for this experiment. Later in this grant year, we will have access to the data in order to process it for the atmospheric parameters, particularly the microwave absorptivity, which is related to the abundance of gaseous H_2SO_4.

IV. PUBLICATIONS AND INTERACTION WITH OTHER INVESTIGATORS

At the beginning of the grant year, we published 2 papers in the Journal of Geophysical Research: Planets (special issue on Laboratory Research for Planetary Atmospheres). The first is entitled "Modeling of the Millimeter-Wave

Emission of Jupiter Utilizing Laboratory Measurements of Ammonia (NH_3 Opacity" by Joiner and Steffes (1991a). The second is entitled "Laboratory Measurement of the Millimeter-Wave Properties of Liquid Sulfuric Acid (H_2SO_4)" by Fahd and Steffes (1991a). We have also had a paper accepted by the IEEE Transactions on Microwave Theory and Techniques entitled "Search for Sulfur (H_2S) on Jupiter at Millimeter Wavelengths," by Joiner and Steffes (1992) describing our observations of Jupiter at 1.4 mm, and the accompanying laboratory measurements of H_2S at that wavelength. It will be published this summer in a special issue on "Microwaves in Space," commemorating the International Space Year. Finally, we have had a paper accepted by Icarus describing our laboratory measurements of the microwave and millimeter-wave opacity of gaseous SO_2 in a CO_2 atmosphere. This paper is entitled "Laboratory Measurements of the Microwave and Millimeter-Wave Opacity of Gaseous Sulfur Dioxide (SO_2) under Simulated Conditions for the Venus Atmosphere," by Fahd and Steffes (1992).

Also, at the beginning of grant year (November 3 - November 8, 1991), we attended the annual DPS/AAS Meeting and the accompanying Third International Conference on Laboratory Research for Planetary Atmospheres, and presented 6 papers (Steffes et al., 1991; Fahd and Steffes, 1991a; Ragent et al., 1991; Fahd and Steffes 1991c; Jenkins and Steffes, 1991; and Joiner and Steffes, 1991). Reprints are included as Appendices.

Finally, as this research program has progressed, the number of graduating Ph.D.'s has increased. In the first half of this grant year, Joanna Joiner received her Ph.D. Copies of her thesis, entitled "Millimeter-Wave Spectra of the Jovian Planets" (Joiner, 1991) were forwarded to NASA in September 1991.

Similarly Jon M. Jenkins received his Ph.D. in March 1992. His thesis, entitled "Variations in the 13 cm Opacity below the Main Cloud Layer in the Atmosphere of Venus Inferred from Pioneer-Venus Radio Occultation Studies: 1978 - 1987" (Jenkins, 1992) was supported by the Pioneer Venus Guest Investigator Program and supplementally by the Planetary Atmospheres Program. Copies were forwarded to NASA in March. Finally, Antoine K. (Tony) Fahd is currently preparing his Ph.D. dissertation, entitled "Study and Interpretation of the Millimeter-Wave Spectrum of Venus."

V. CONCLUSION

In the remainder of this grant year (ending October 31, 1992) we will apply this new formalism for computing the opacity from gaseous H_2SO_4 to our radiative transfer model for Venus which we described in Fahd and Steffes (1992). Already this work has shown that there are specific millimeter-wave frequencies which are especially sensitive to the abundance of H_2SO_4 vapor in the Venus atmosphere. In fact, variations in the abundance of gaseous H_2SO_4 can explain the variations in the 2.6 mm Venus emission reported by dePater et al., (1991). In August, we plan to report on our work at the International Colloquium on Venus to be held in Pasadena. Similarly, we will present these results and additional results from the Magellan experiment at the October DPS/AAS meeting in Munich.

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VII. APPENDICES

APPENDIX I: Poster Paper Presented at the 1991 DPS/AAS Meeting

20.20-P Radio Occultation Studies of the Venus Atmosphere with the Magellan Spacecraft

P.G. Steffes, J.M. Jenkins (Georgia Inst. of Tech.), R.S. Austin, S.W. Asmar (JPL/CalTech), G.L. Tyler (Stanford Univ.), and E.H. Seale (Martin Marietta)

While primarily designed for radar studies of the Venus surface, the high radiated power (EIRP) from the Magellan spacecraft makes is an ideal transmitter for use in a bistatic radio occultation measurement of the refractivity and absorptivity of the Venus atmosphere. The experiment (conducted 10/5/91) involved transmissions at 2.3 GHz and 8.4 GHz (13 cm and 3.6 cm, respectively), and was performed during spacecraft ingress for 3 orbits. Since the stability of the spacecraft transmitter is critical for accurately determining the doppler shift and amplitude attenuation created as the ray penetrates the atmosphere, the spacecraft transmitter was locked to a 2.1 GHz uplink from DSS-43 (Tidbinbilla, Australia), which also received the signals. Because of the high gain of the spacecraft antenna, and the significant ray bending in the deep Venus atmosphere, a spacecraft tracking maneuver was designed to keep the spacecraft antenna pointed in the direction of the refracted ray path back to earth. This tracking maneuver, plus the high effective isotropic radiated power (EIRP) of the Magellan transmitter is expected to yield 3.6 cm refractivity and absorptivity profiles down to the 42 km altitude and 13 cm profiles down to the altitude of critical refraction (approximately 35 km), once the data is processed. It is also expected that the statistical uncertainties in the derived profiles will be significantly lower than those previously obtained, and will result in extremely accurate profiles of H_2SO_4 (g) abundance.

Figure 1

ATMOSPHERIC RADIO OCCULTATION MEASUREMENTS WITH MAGELLAN AT VENUS

GOALS: OBTAIN REFRACTIVITY AND ABSORPTIVITY PROFILES (13 cm and possibly 3.6 cm) TO LOWEST POSSIBLE ALTITUDES IN THE VENUS ATMOSPHERE IN ORDER TO BETTER CHARACTERIZE SPATIAL AND TEMPORAL VARIATIONS

USE ABSORPTIVITY PROFILES TO CHARACTERIZE ABUNDANCE AND DISTRIBUTION OF GASEOUS H_2SO_4 AND IDENTIFY SPATIAL AND TEMPORAL VARIATIONS OF SAME.

DEVELOP T-P PROFILES FROM REFRACTIVITY PROFILES AND CORRELATE VARIATIONS IN SUB-CLOUD T-P PROFILES WITH VARIATIONS IN H_2SO_4 ABUNDANCE, AND WITH MAPS MADE BY GALILEO NIMS.

ADVANTAGES OVER PIONEER-VENUS RADIO OCCULATION EXPERIMENTS:

MUCH HIGHER EIRP (EFFECTIVE ISOTROPIC RADIATED POWER) FROM MAGELLAN WILL RESULT IN PROFILES WITH SMALLER ERROR BARS AND WILL ALLOW PROBING MUCH DEEPER IN THE ATMOSPHERE. ITS IS EXPECTED THAT AT 13 CM, SIGNAL CAN BE TRACKED DOWN TO THE 35 KM ALTITUDE AND DOWN TO 42 KM AT 3.6 CM. THIS COMPARES WITH 42 and 54 KM, RESPECTIVELY FOR PIONEER-VENUS.

BECAUSE OF THE SHORTER ORBITAL PERIOD, SUCCESSIVE OCCULTATIONS WOULD ONLY BE SPACED BY ABOUT 3 HOURS, THUS "DECOUPLING" THE TIME VARIABILITY FROM THE SPATIAL VARIABILITY. (SEVERAL I.R. OBSERVERS HAVE REPORTED A LARGE FEATURE WHICH SEEMS TO CIRCLE VENUS EVERY 72 HOURS OR SO. WITH TWO OCCULTATION MEASUREMENTS MADE ONLY HOURS APART, THE SPATIAL EDGE OF SUCH A FEATURE MIGHT BE DETECTED.)

PIONEER VENUS WILL ENTER THE VENUS ATMOSPHERE NEXT YEAR.

SUPPORT REQUIRED:

DSN 70-METER ANTENNA (S-BAND UPLINK, 80KW; OPEN LOOP RECEIVER FOR S-BAND DOWNLINK; AND (AS AN OPTION), OPEN LOOP RECEIVER FOR X-BAND DOWNLINK)

SPACECRAFT TRACKING MANEUVER, SO AS TO KEEP HGA POINTED TOWARD THE LIMB OF THE PLANET (AND THUS THE RAY PATH BACK TO EARTH).

A GOOD CHARACTERIZATION OF THE TRACKING MANEUVER, SO THAT VARIATIONS IN RECEIVED AMPLITUDE DUE TO SPACECRAFT MOTION ARE NOT MISTAKEN FOR ATMOSPHERIC EFFECTS.

P.STEFFES

RADIOSCIENCE EXPERIMENT REQUIREMENTS

IMPLEMENTATION:
- NON-RSA ORBITS (MGN ORBITS 3212, 3213, & 3214)
- TURN BETWEEN TWO FIXED ATTITUDES
- NEARLY CONSTANT RATE OF 0.083°/SEC
- DURATION OF APPROX 180 SEC

SPACECRAFT:
- X-BAND DOWNLINK WITH HIGH-RATE MODULATOR OFF (X-BAND TELEMETRY LEFT ON)
- S-BAND DOWNLINK WITH TELEMETRY MODULATOR OFF
- RECORD S/C RECEIVED SNR
- RECORD S/C ATTITUDE ERROR DATA ON TAPE FOR MANEUVER RECONSTRUCTION

DSN:
- 70M STATION
- 80kWATTS S-BAND UPLINK (60 dB MARGIN AT MANEUVER START)
- OPEN LOOP RECEIVER TRACKING
- PERFORM TEST (RECORD S/C DOWNLINK WITH RADIOSCIENCE RECEIVERS) ON 19, AUGUST
- 5/6 OCT: RECORD BOTH POLARIZATIONS

NAV:
- POST-MANEUVER UPDATES TO PERIAPSIS CROSSING TIMES

ANCILLARY:
- NEED BOTH S AND X-BAND ANTENNA PATTERNS (AT LEAST SEVERAL CUTS)

FIGURE 3:

RADIOSCIENCE EXPERIMENT PROFILE

(MGN ORBITS 3212, 3213, & 3214 : 5OCT91 and 6OCT91)

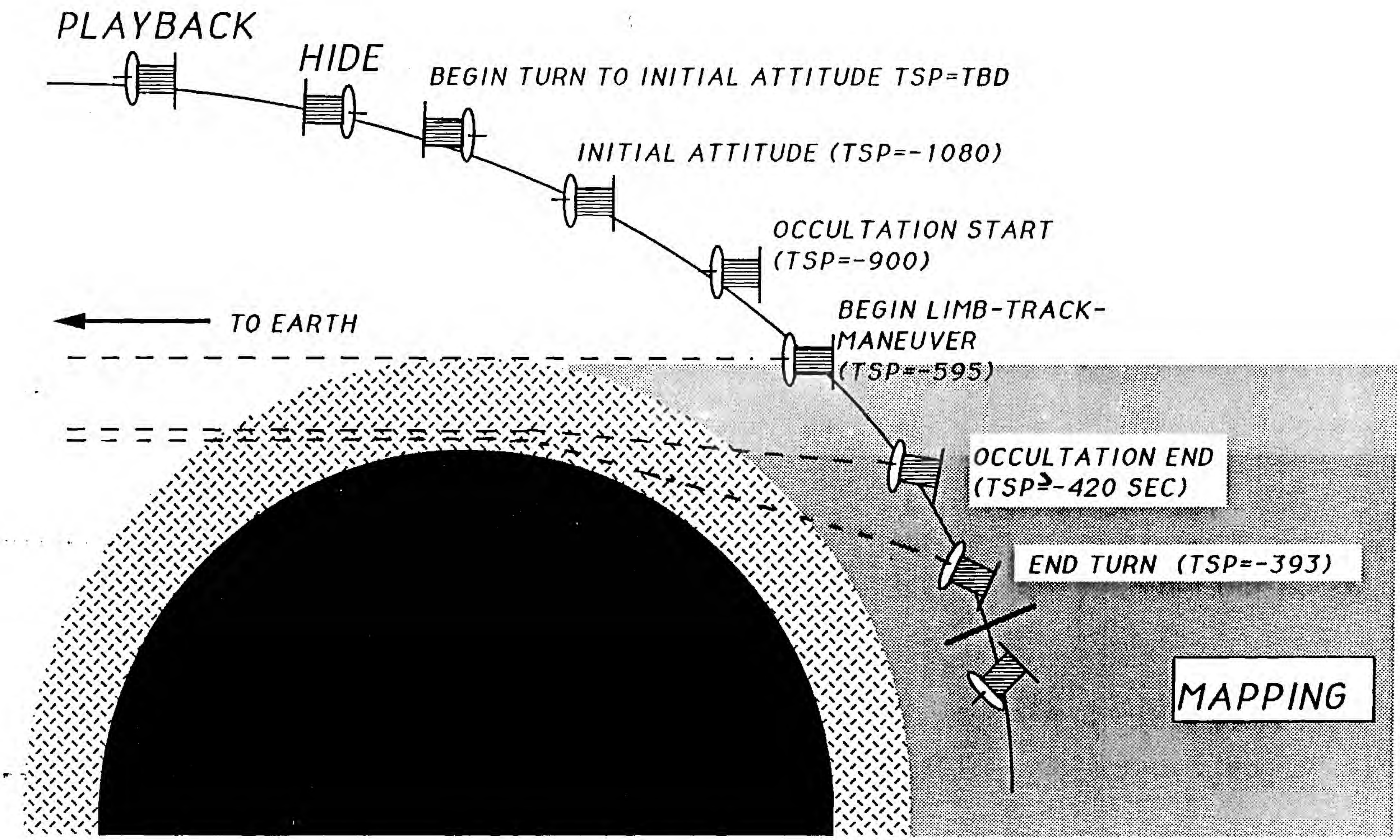


Figure 4: Predicted bending angle of ray (in radians) as a function of time at the receiving station

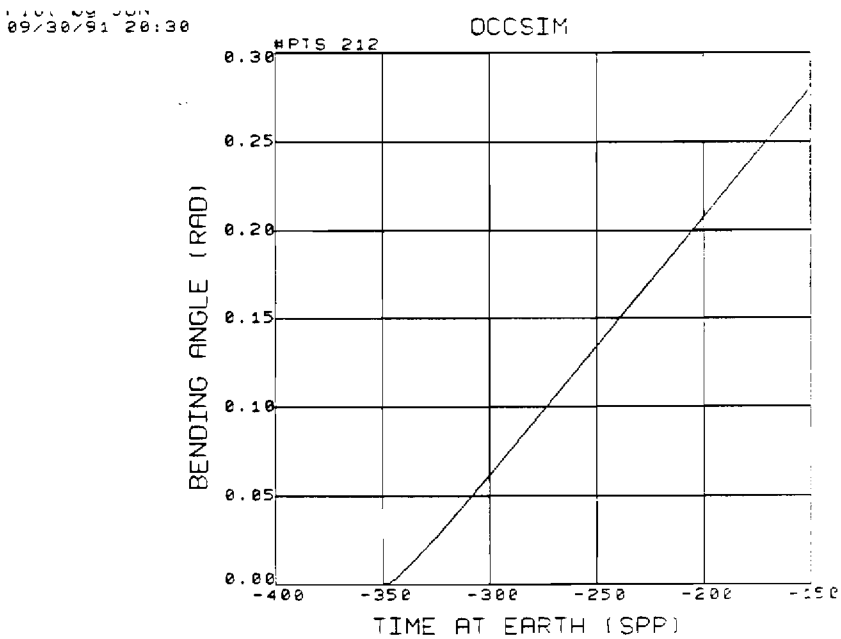


Figure 5: Antenna Pattern for Magellan at X-Band (3.6 cm). The narrowness of the beam requires that the spacecraft be re-pointed in order to keep the antenna directed toward the refracted path back to Earth.

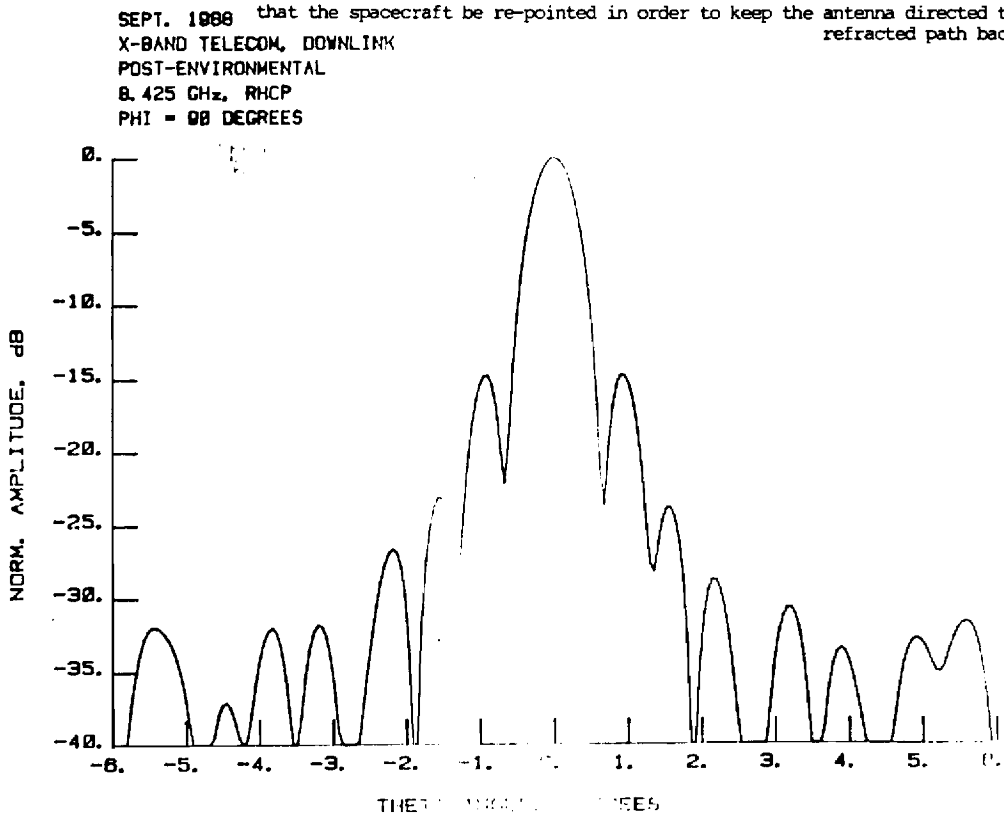
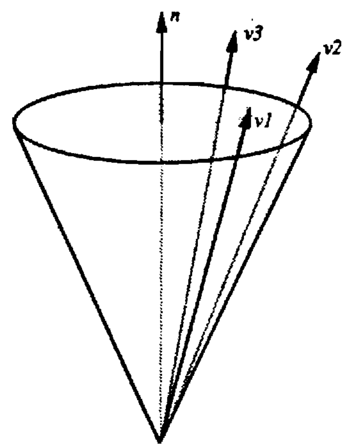


Figure 6a: Antenna tracking maneuver design using conical track

Preliminary Limb-Tracking Maneuver Design -- Earth Track Cone Determination



- In a plane, 3 points define a circle
- In space, 3 vectors define a cone
- We want the axis of a cone that "fits" the Earth image vectors well -- this will be the eigenvector for the rotation to scan the HGA through the vectors
- For simplicity, I'll define a cone using 3 hand-picked vectors (first, last, middle) -- don't want to derive a 3-D least-squares algorithm just yet...

Figure 6b: **Path Fit Error (Cross-Track) Over Time**

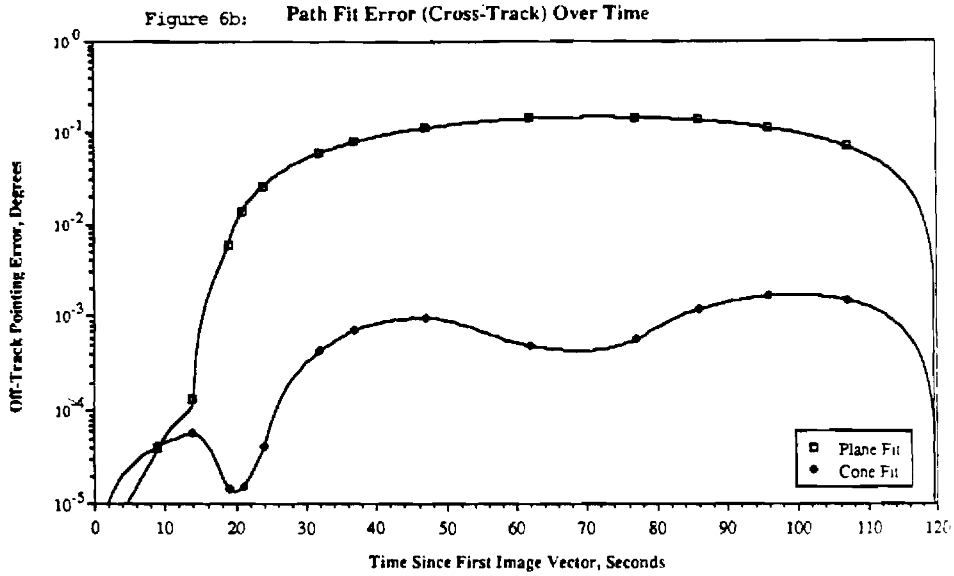


Figure 6c: Along-Track Pointing Error Over Time

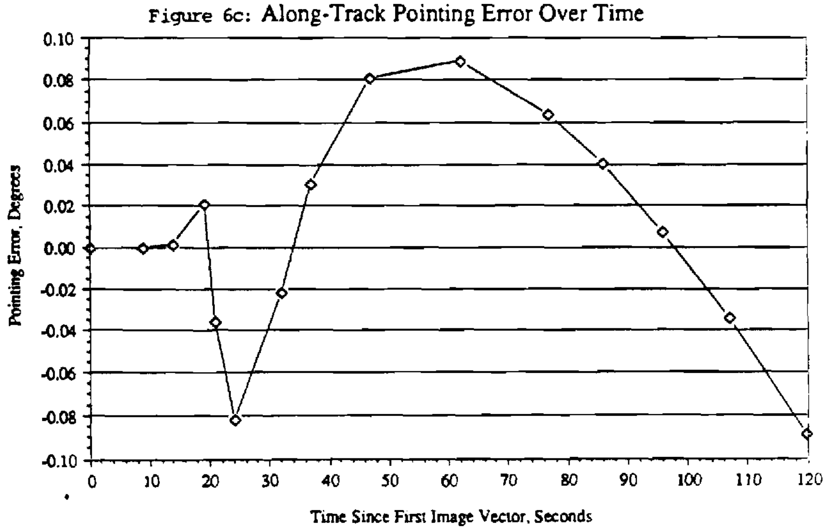
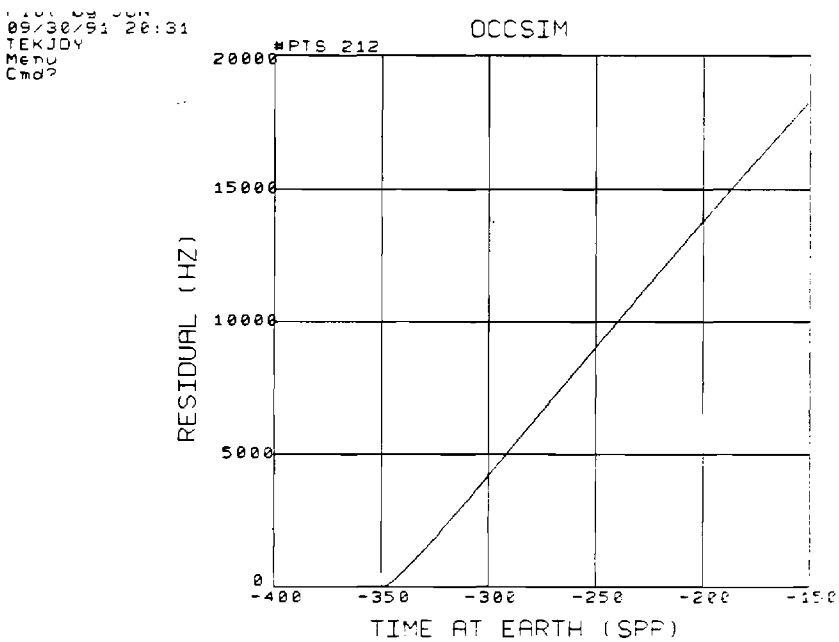
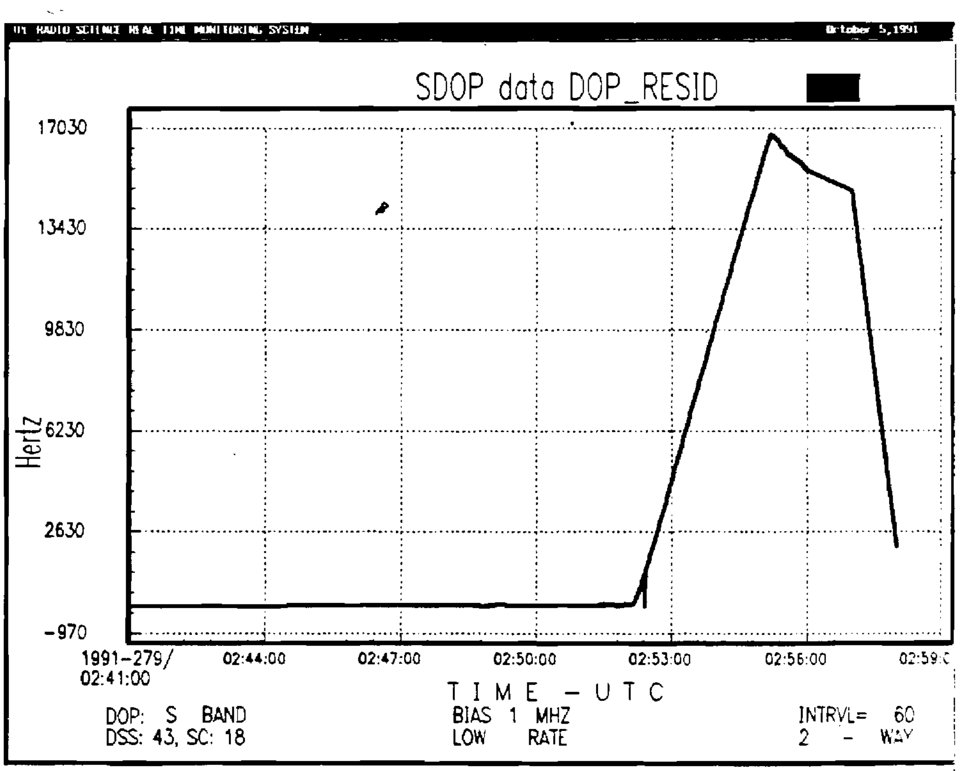


Figure 7: Excess doppler (in addition to that expected from normal motion of spacecraft and earth) encountered during radio occultation experiment as a function of time at the receiving station (Note: SPP is short for Seconds Past Periapsis)





7b - S-Band Doppler actually measured -

Figure 8: Solid line: Relative amplitude of received signal as a function of time at the receiving site. (predicted)
Upper dotted line: Portion of amplitude reduction due to atmospheric absorption (predicted)
Lower dotted line: Portion of amplitude reduction due to refractive defocussing (predicted

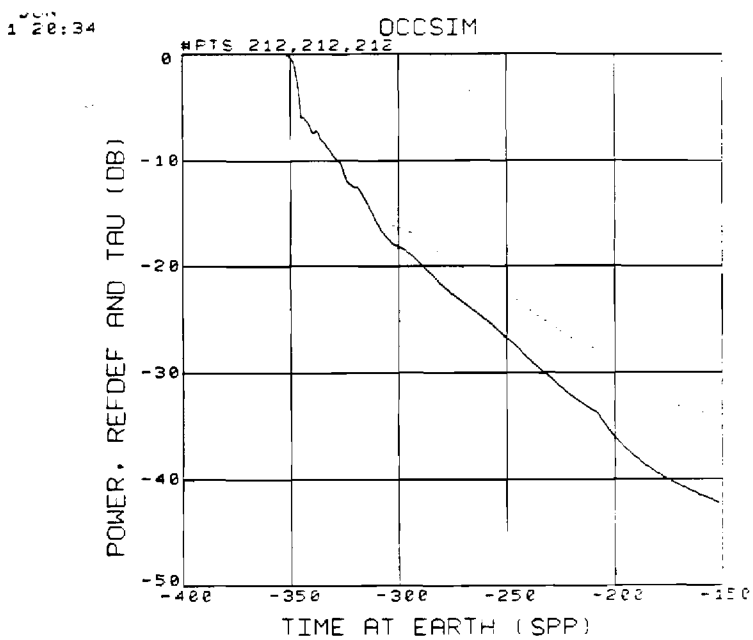


Figure 9: Radius of deepest ray penetration versus time of reception at earth station.

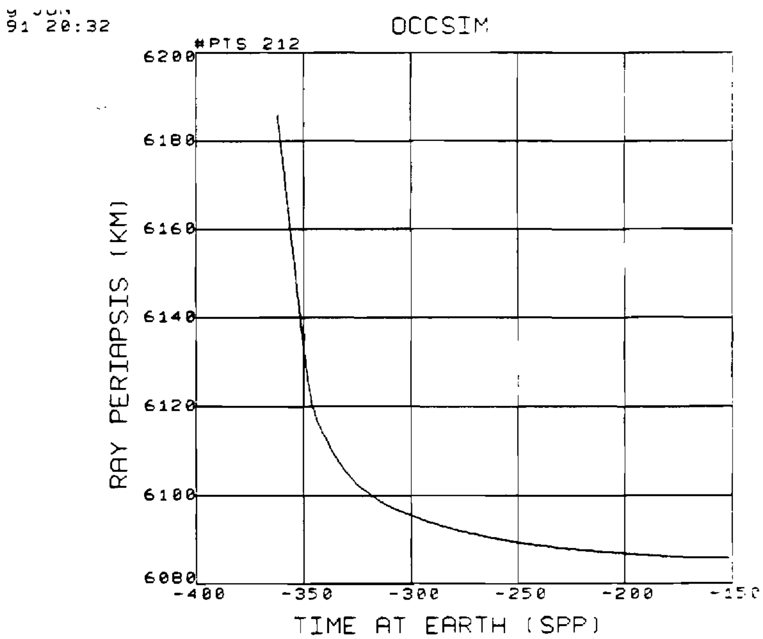


Figure 10: Radius of deepest ray penetration versus time of reception at earth station, expanded at the deepest points probed. Rate of penetration of ray is drastically reduced in the deep atmosphere.

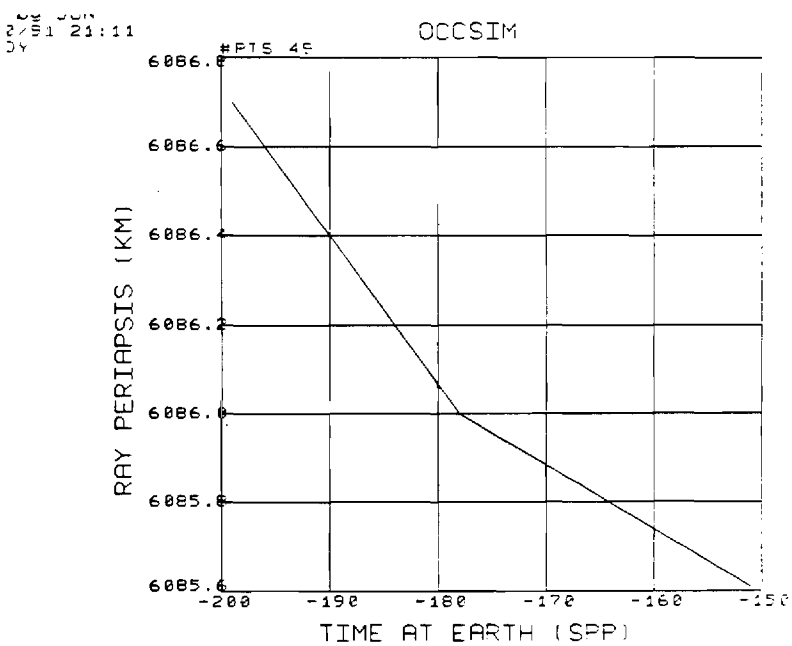
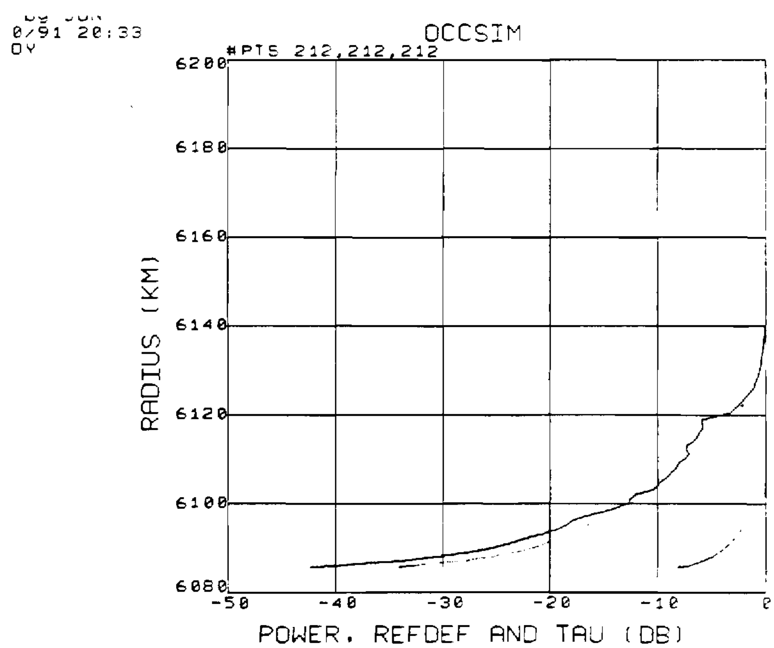


Figure 11: Solid line: Relative amplitude of received signal as a function of depth probed (predicted).
Leftmost dotted line: Refractive defocussing as a function of depth probed
Rightmost dotted line: Atmospheric absorption as a function of depth probed



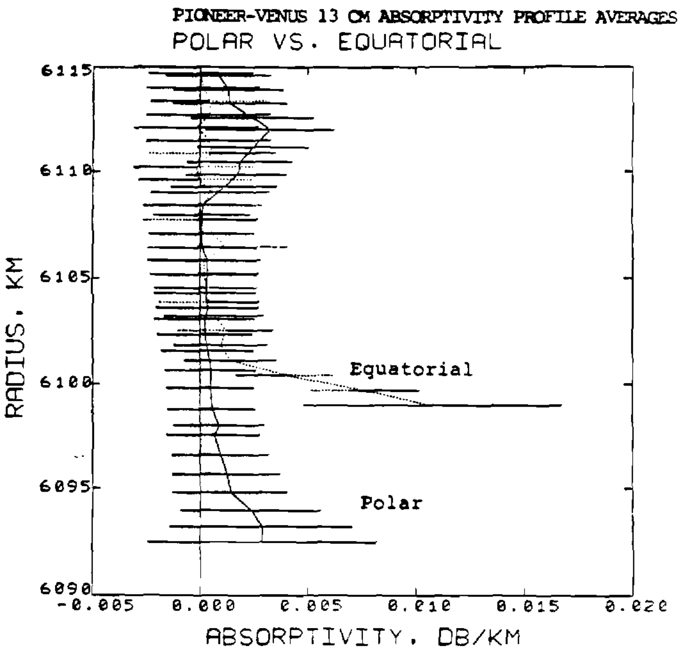


Figure 12.: Average 13 cm opacity profiles obtained for the equatorial region (dotted line) and the polar region (solid line) during Season 10*. These absorptivities are related to the abundance of gaseous H_2SO_4. Much deeper profiles could be obtained with much smaller error bars if the Magellan spacecraft were used rather than Pioneer Venus.

*Season 10: 8/86 - 1/87

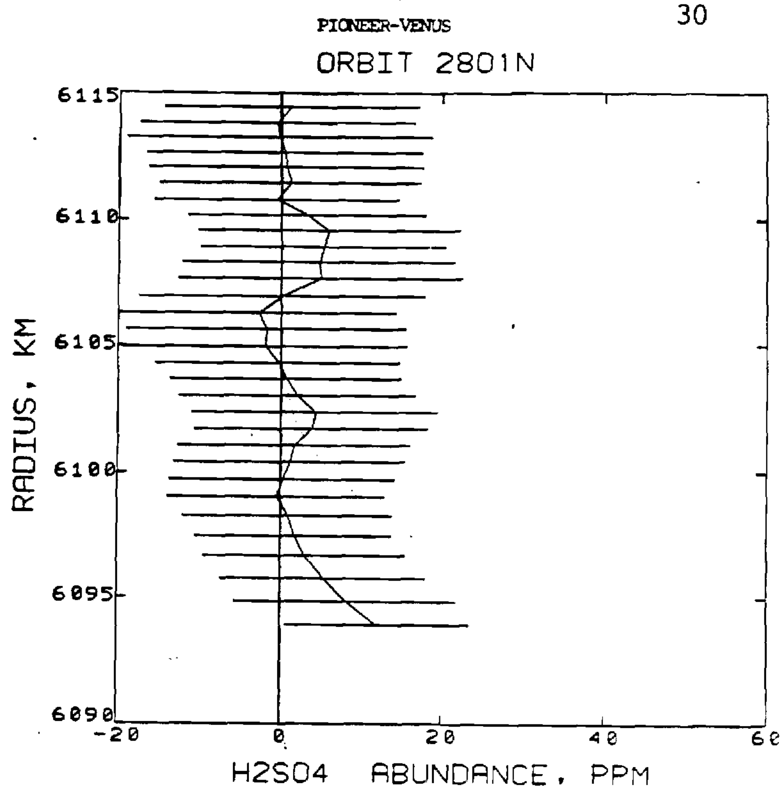
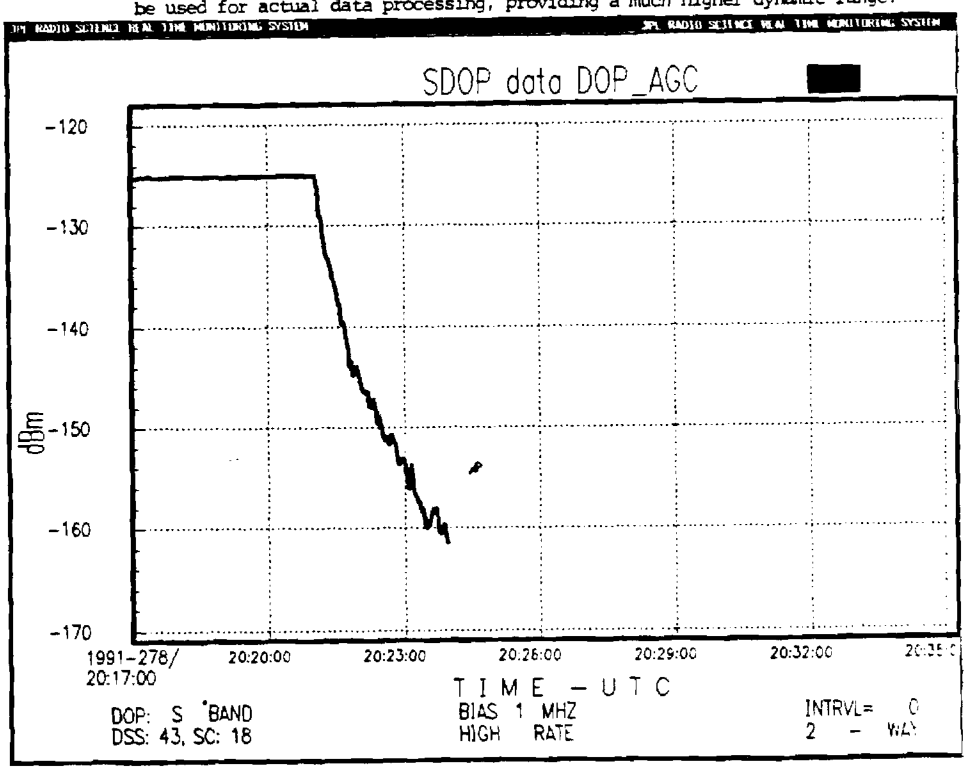


Figure 13: Gaseous H_2SO_4 abundance as a function of rad measured for orbit 2801N, which occurred on August 1986 at 40.8°N (solid line) and the abundance expec from saturation vapor pressure (dotted line). The relatively large error bars could be reduced by using the Magellan orbiter. Likewise, the profile could be extended several kilometers deeper.

Figure 14: Actual received signal amplitude measured during Magellan Radio Occultation Experiment using the "closed loop" (lower sensitivity) receiver at DSS-43. (Compare with figure 8). A more sensitive "open loop" receiving system will be used for actual data processing, providing a much higher dynamic range.



UPDATE

MAGELLAN RADIO OCCULTATION EXPERIMENT

5 OCT 91 - 6 OCT 91

DEEPEST ALTITUDE PROBED (13 CM- WAVELENGTH/ S-BAND): 33.5 KM*

DEEPEST ALTITUDE PROBED (3.6 CM- WAVELENGTH/ X-BAND): 34.8 KM*

(*RELATIVE TO MEAN VENUS RADIUS OF 6052 KM)

MAXIMUM BENDING ANGLES MEASURED:

S-BAND: 16 DEGREES

X-BAND: 11.5 DEGREES

MAGELLAN CYCLE 3 -- APOAPSIS RADIO OCCULTATION EXPERIMENTS (Now thru Mar 10)

1. Data taken at DSN with no changes in spacecraft operation.
2. Experiment will only be conducted at X-band (3.6 cm) and with no limb-tracking maneuver. Hence, the signal will only be received down to an altitude of about 65 km, before it is lost due to ray path bending moving the ray out of the main beam of the spacecraft antenna.
3. Initial trials (upload 2038) will probe latitudes from -88°S up to -78° S. Data will be taken with closed loop receiver.
4. The second trial (upload 2052) will probe latitudes from -31°S to the equator. The open loop receiver will also be available for these measurements. (Configuration will allow efficient storage of longer data.)
5. The main science product will consist of vertical profiles of atmospheric refractivity, which is related to the atmospheric temperature-pressure profile. It will provide important information about southern hemisphere middle atmosphere dynamics.

MAGELLAN CYCLE 4 -- APOAPSIS RADIO OCCULTATION EXPERIMENTS (11/18/92-12/31-92)

1. Experiment to be conducted at both S-band (2.3 GHz) and X-band (3.6cm) with spacecraft tracking the limb of the planet using a fitted turn (Similar to the Oct 1991 experiment) rather than using MQPC.

2. The experiment will require 70-m DSN support, and will require data recording for about 16 minutes per occultation. (DSP/open loop receiver)

3. Complete profiles of refractivity (related to atmospheric temperature and pressure, as well as to ionospheric density) and absorptivity (related to abundance of gaseous H_2SO_4) will be obtained for latitudes from -88°S to equatorial, and down to altitudes of 33 km.

4. This study will be the first extended study of the Southern Hemisphere's atmosphere.

APPENDIX II: Abstracts of other papers given at 1991 DPS/AAS Meeting.

01.19-P

Search for H_2S on Jupiter at millimeter wavelengths: Observations and Laboratory Measurements

J. Joiner, P. G. Steffes (Georgia Institute of Technology)

Sulfur has not yet been detected on the Jovian planets. Radiative transfer models suggest that millimeter wavelength pressure-broadened H_2S lines might be detectable on Jupiter. Therefore, we attempted to detect the 1.4 mm (217 GHz) H_2S line using the 10.4 m Caltech Submillimeter Observatory (CSO). Although we were unable to detect H_2S, we were able to obtain a reliable brightness temperature of Jupiter using Mars as the calibration standard.

The spectral resolution of conventional millimeter receivers ($\Delta\nu/\nu = 1 \times 10^{-4}$) is too high for detecting pressure-broadened H_2S lines ($\Delta\nu/\nu = 0.1$). We therefore operated the CSO receiver (DSB with 500 MHz total bandwidth and 2.8 GHz side band separation) as a photometer to measure the differential emission between two frequencies, one near the line center (LO = 215.3 GHz, 1.31 mm) and one off the line center (LO = 229.6 GHz, 1.39 mm). Our observed Jovian brightness temperatures at the two frequencies were 175.0 ± 2.5 and 178.1 ± 13, respectively. We are unable to place a tight upper limit on Jupiter's H_2S abundance due to the large uncertainties.

We have also completed a laboratory measurement of H_2S absorption at 1.4 mm in a simulated Jovian atmosphere. The measured hydrogen-broadened linewidth of the $J'_{K'_{-1}K'_{+1}} - J_{K_{-1}K_{+1}} = 2_{0,2} - 2_{1,1}$ H_2S line was 2.0 ± 0.5 GHz/bar (2.6 ± 0.7 MHz/torr).

This work was supported by NASA grant NAGW-533. This material is also based on work supported by the Georgia Tech Space Grant Consortium.

20.01

Correlation of Earth-Based NIR Imagery and Pioneer-Venus Orbiter Imagery and Data

B. Ragent (SJSUF), L. Travis (NASA/GISS), D. Crisp (JPL/CIT), D. Allen (AAO), P. Steffes, J. Jenkins (GIT), G. Deardorff, Y. Hung (Sterling)

Dark side images of Venus at wavelengths near 1.7 and 2.3 microns have been obtained at a number of observatories during periods near the past few inferior conjunctions, as well as from the Galileo spacecraft in February, 1990. Favorable viewing opportunities during some of these periods also allowed at least partial images at shorter wavelengths and other data to be obtained from experiments aboard the Pioneer-Venus Orbiter (PVO). Comparisons of these different sets of images help to describe the morphology of cloud structures and regions of atmospheric activity. PVO radio transmitter occultation measurements obtained during the period near the 1991 inferior conjunction will yield vertical profiles of sulfuric acid vapor concentrations in regions near the base of the clouds. Variations in opacities in the near-ir images are presumably due to variations in the number density of large particles in the lower regions of the clouds. Anticorrelation of these opacities with the variation in sulfuric acid concentration from equilibrium values will argue strongly that the large particles are composed of sulfuric acid.

20.10

Laboratory Measurements of the Millimeter-Wave (3 mm) Opacity of Gaseous SO_2 under Simulated Conditions of the Middle Atmosphere of Venus.

A.K. Fahd, P.G. Steffes (Georgia Institute of Technology)

Gaseous sulfur dioxide has long been recognized as one of the dominant absorbers in the Venus atmosphere at microwave frequencies (f< 30 GHz). However, its effect on the millimeter-wave emission is not fully understood. This is due to the lack of any measurements of its opacity at millimeter-wavelengths (shorter than 1 cm). Previously, researchers (Steffes & Eshleman, Icarus 1981, and Janssen & Poynter, Icarus 1981) have reported that the absorption coefficient of gaseous SO_2 in a CO_2 atmosphere was consistent with an f^2 (f=frequency) dependence from 1 to 6 atmospheres. Recently, Fahd & Steffes (DPS, 1990) showed that the f^2 dependence may be valid for frequencies at which the measurements were made, however, the simple extrapolation of SO_2 absorptivity to a higher frequency region (millimeter wavelengths) using the f^2 dependence is not valid, thus the need for a laboratory measurement. The experimental configuration used to measure the SO_2 opacity in a CO_2 atmosphere consists of a Fabry-Perot resonator operating at 94 GHz. The absorptivity of SO_2/CO_2 is measured by monitoring the effects of the gas mixture on the resonant frequency and the bandwidth of the resonator. The results of our measurements show a close agreement with the absorbtivity predicted from a Van Vleck-Weisskopf (VVW) formalism and show a deviation from the f^2 dependence proposed by other researchers. In short, this work has demonstrated that the Van Vleck-Weisskopf formalism appears to provide a good estimate of the absorption of SO_2 in a CO_2 atmosphere at millimeter wavelengths in contrast to the f^2 dependence previously suggested. In addition, our results are incorporated into a radiative transfer model to infer a new abundance profile of gaseous SO_2 in the middle atmosphere of Venus based on existing microwave emission of Venus. Finally, the developed model is used to determine the effects of gaseous SO_2/CO_2 mixture on the millimeter-wave spectrum of Venus.

* This work was supported by the Planetary Atmospheres Program of the National Aeronautics and Space Administration under grant NAGW-533.

20.14-P

Comparison of Kalman and Wiener Filtering Techniques for Processing Pioneer Venus Radio Occultation Data

J.M. Jenkins, and P.G. Steffes (Georgia Institute of Technology)

Reduction of amplitude data from radio occultation experiments to yield vertical profiles of atmospheric absorptivity involves the application of an Abel-type inverse transform. Because the inverse Abel transform (IAT) is weakly ill-posed (under a change of variables it corresponds to half-order differentiation) the data must be smoothed prior to application of the transform. Otherwise, the IAT amplifies random noise preferentially above the actual signal in the noise-corrupted data. In this study, three techniques are applied to synthetic radio occultation data for comparison: a Kalman filter approach (Hansen and Law, 1985), a Wiener filtering approach (Anderssen, 1976) and a least-squares polynomial approach (Minerbo and Levy, 1969). The results of each method are compared for stability and absolute accuracy against a model atmosphere. In addition to yielding stable results without oversmoothing, the Kalman and Wiener filtering techniques hold potential to reduce estimated uncertainties on derived profiles. Results of applying these methods to actual radio occultation data from Pioneer Venus obtained during Season 10 (1986-87) are also presented.

* This material is based on work supported in part under a National Science Foundation Graduate Fellowship.

APPENDIX III: Paper presented at the Third International Conference on Laboratory Research for Planetary Atmospheres.

LABORATORY MEASUREMENT OF THE MILLIMETER-WAVE OPACITY OF GASEOUS SULFURIC ACID (H_2SO_4) UNDER VENUS-LIKE CONDITION.

A.K. Fahd, P.G. Steffes
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, Ga. 30332

Recent observations of the millimeter-wave emission from Venus at 115 GHz (2.6 mm) have shown significant variations in the continuum flux emission (de Pater et al., Icarus 1991) which may be attributed to the variability in the abundances of the absorbing constituents in the middle atmosphere of Venus. Such constituents include gaseous H_2SO_4 ,SO_2 , and liquid sulfuric acid (cloud condensates). Recently, Fahd and Steffes (DPS 91, and JGR (Planets) 1991) have shown that the effects of liquid H_2SO_4 and gaseous SO_2 cannot completely account for this measured variability in the millimeter-wave emission of Venus. To fully understand potential sources of this variation, one needs to study the effects of gaseous sulfuric acid on the emission of Venus. However, the determination of the millimeter-wave opacity of gaseous H_2SO_4 is difficult since no laboratory measurements have been performed for Venus-like conditions. As a result, the laboratory measurements of the opacity of gaseous sulfuric acid in a CO_2 atmosphere at millimeter-wavelengths are greatly needed. Laboratory measurements of the opacity of gaseous sulfuric acid in a CO_2 atmosphere are currently being performed at 94 GHz. The experimental setup employs a free-space transmission configuration. The cell containing the gaseous mixture is placed in a temperature controlled chamber. The opacity of the gas mixture is measured at 550, 570 and 590 K for 1 and 2 Atm total pressure. The results will then be fitted to a model to account for the opacity of the gas mixture in the millimeter-wave region. This will then be incorporated into a radiative transfer model to interpret the measured variations in the millimeter-wave emission of Venus.

* This work is supported by the Planetary Atmospheres Program of the National Aeronautics and Space Administration under grant NAGW-533.

E21-623
18

REPORT

TO THE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

SEMIANNUAL STATUS REPORT #18

for

GRANT NAGW-533

LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

Paul G. Steffes, Principal Investigator

May 1, 1992 through October 31, 1992

Submitted by

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I. INTRODUCTION

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing atmospheric constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or using laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. For example, laboratory measurements performed by Fahd and Steffes (1992a), under Grant NAGW-533, have shown that the opacity from gaseous SO_2 under simulated Venus conditions can be well described by the Van Vleck-Weisskopf lineshape at wavelengths shortward of 2 cm, but that the opacity of wavelengths greater than 2 cm is best described by a different lineshape that was previously used in theoretical predictions. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements <u>and</u> to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

II. LABORATORY MEASUREMENTS

A. Venus

An important source of information regarding the Venus atmosphere is the increasing number of high spatial resolution millimeter-wavelength emission measurements which have been recently conducted. (See, for example, de Pater *et al*., 1991a). Correlative studies of these measurements with Pioneer-Venus radio occultation measurements (Jenkins and Steffes, 1991), with newly conducted Magellan radio occultation experiments (Steffes *et al*., 1992b), and with our longer wavelength emission measurements (Steffes *et al*., 1990), will provide new ways for characterizing temporal and spatial variations in the abundance of both gaseous H_2SO_4 and SO_2, and for modeling their roles in the subcloud atmosphere. However, unambiguous results require that we have dependable knowledge of the microwave and millimeter-wave opacity of gaseous and liquid H_2SO_4, and of gaseous SO_2 under Venus conditions.

While some laboratory measurements of the microwave absorption properties of gaseous SO_2 under simulated Venus conditions were made at 13 cm and 3.6 cm wavelengths by Steffes and Eshleman (1981), no measurements have been made at shorter wavelengths. As a result, we conducted laboratory measurements of the 13 cm, 1.35 cm, and 3.2 mm opacity of gaseous SO_2. These measurements and their applications have been described in a paper by Fahd and Steffes (1992a); which appeared in the June 1992 issue of Icarus. (Reprints were forwarded to NASA in July 1992.) The final experiment needed for proper interpretation of the Venus millimeter-wavelength continuum was laboratory measurement of the opacity of gaseous H_2SO_4. We recently completed such measurements, and have developed a formalism for computing the millimeter-wave opacity of gaseous H_2SO_4. We have applied this formalism to our millimeter-wavelength radiative transfer model for Venus, and have found that there are specific millimeter-wave frequencies which are especially sensitive to the abundance of H_2SO_4 vapor in the lower Venus atmosphere. This work was presented at the International Colloquium on Venus (Pasadena, CA, August 10-12, Fahd and Steffes, 1992b), and is attached as Appendix A.

B. Outer Planets

Because of the large abundance of ammonia in Jupiter's atmosphere, it has not been possible to detect either the microwave or millimeter-wavelength opacities from the gaseous H_2S thought to exist deep in that atmosphere. (See, for example, Joiner et al., 1992) However, ammonia is substantially depleted in the atmospheres of Uranus and Neptune, and it has been suggested by de Pater et al. (1991b) that the pressure broadened absorption from H_2S significantly affects the centimeter wavelength emission from those planets. In order to accurately infer the abundance and distribution of H_2S in the deep atmospheres of Uranus and Neptune, either from their centimeter radio emission or from radio occultation measurements, accurate laboratory measurements of the microwave opacity from gaseous H_2S under simulated conditions for the outer planets must be conducted at centimeter wavelengths. Such a laboratory measurement program has recently been initiated at Georgia Tech, in which measurements of the opacity of gaseous H_2S in a H_2/He atmosphere are conducted at pressures from 1 to 6 Bars, at temperatures from 173 to 294K, and at frequencies of 2.25, 8.5, and 21.7 GHz. While (to date) measurements have only been conducted at room temperature, our results already indicate that the centimeter wavelength opacity from gaseous H_2S

in an H_2/He atmosphere significantly exceeds that which would be predicted using the Van Vleck-Weisskopf formalism, even when the newly measured value for H_2S line broadening (Joiner et al., 1992) is used. These preliminary results were reported in a paper presented at the Fourth International Conference on Laboratory Research for Planetary Atmospheres (October 1992, Munich) which is attached as Appendix B (Steffes et al., 1992a).

III. RADIO OCCULTATION STUDIES OF THE VENUS ATMOSPHERE WITH THE MAGELLAN SPACECRAFT

We have also been successful in this grant year in conducting a radio occultation experiment with the Magellan Spacecraft. This was the first atmospheric work conducted with Magellan and the atmosphere was probed to deeper levels than was possible with the less powerful Pioneer-Venus Orbiter radio transmission system. This experiment was conducted on October 5, 1991, and consisted of three entry occultation experiments. This successful demonstration has shown the feasibility of using the Magellan spacecraft to provide highly accurate atmospheric refractivity and absorptivity profiles, which in turn, can be used to determine profiles of temperature, pressure, and gaseous H_2SO_4 abundance in the Venus atmosphere. The preliminary results from this experiment were presented at the 1992 Meeting of the Division for Planetary Sciences of the American Astronomical Society (DPS/AAS) in Munich, Germany (October 12-17, 1992). A copy of this presentation is attached as Appendix C (Steffes et al., 1992b). In the future, we intend to use Magellan radio occultation data as part of an integrated multi-spectral analysis of Venus atmospheric data.

IV. PUBLICATIONS AND INTERACTION WITH OTHER INVESTIGATORS

In the second half of this grant year (May 1, 1992 - October 31, 1992), we published two papers. The first was published in IEEE Transactions on Microwave Theory and Techniques (special issue commemorating the International Space Year) and is entitled "Search for Sulfur (H_2S) on Jupiter at Millimeter Wavelengths" by Joiner, Steffes, and Noll (June, 1992). It describes our observations of Jupiter at 1.4 mm and the accompanying laboratory measurements of H_2S at that wavelengths. The second paper was published in Icarus in June and is entitled "Laboratory Measurements of the Microwave and Millimeter-Wave Opacity of Gaseous Sulfur Dioxide (SO_2) under Simulated Conditions for the Venus Atmosphere," by Fahd and Steffes (1992a). Reprints of both papers have been forwarded to NASA Headquarters, and distributed to interested researchers at JPL, NASA centers, and universities.

In August, we attended the International Colloquium on Venus held in Pasadena, California, and presented two papers. The first was entitled "Understanding the Variation in the Millimeter-Wave Emission of Venus" (Fahd and Steffes, 1992b) and is attached as Appendix A. The second was entitled "Long-Term Variations in the Abundance and Distribution of Sulfuric Acid Vapor in the Venus Atmosphere Inferred from Pioneer Venus and Magellan Radio Occultation Studies" by Jenkins and Steffes (1992) which presented recent results from Magellan and Pioneer-Venus radio occultation studies. In conjunction with this conference, a press conference was held on August 11 at which we described the successful radio occultation experiment conducted with Magellan. Antoine Fahd's paper reported work conducted as part of this doctoral dissertation, which was completed in May.

Copies of the dissertation were forwarded to NASA as Technical Report 1992-1.

In October we attended the 24th meeting of the Division for Planetary Sciences of the American Astronomical Society (DPS/AAS) and the accompanying Fourth International Conference on Laboratory Research for Planetary Atmospheres. Both papers presented (Steffes et al. 1992a and 1992b) are attached as Appendices B and C.

V. CONCLUSION

In the next grant year, we will continue our laboratory measurements of the centimeter wavelength opacity of gaseous H_2S under simulated conditions for the outer planets. Measurements at temperatures as low as 173K will be conducted. When all of the data is obtained, a new formalism for computing the microwave absorption from H_2S under conditions for the outer planets will be developed. This formalism will then be integrated into our radiative transfer model for the outer planets so as to study the effects of H_2S on their centimeter wavelength emission. Similarly, we will continue to obtain microwave absorptivity profiles for the Venus atmosphere from Magellan radio occultation experiments, and use them to develop profiles of H_2SO_4 vapor abundance.

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VII. APPENDICES

APPENDIX A:
Presented at the International Colloquium on Venus, August 10, 1992

UNDERSTANDING THE VARIATION IN THE MILLIMETER-WAVE EMISSION OF VENUS; Antoine K. Fahd and Paul G. Steffes, School of Electrical Engineering, Georgia Institute of Technology, Atlanta, Ga. 30332.

Recent observations of the millimeter-wave emission from Venus at 112 GHz (2.6mm) have shown significant variations in the continuum flux emission [1] which may be attributed to the variability in the abundances of absorbing constituents in the Venus atmosphere. Such constituents include gaseous H_2SO_4, SO_2, and liquid sulfuric acid (cloud condensates). Recently, Fahd and Steffes [2,3] have shown that the effects of liquid H_2SO_4 and gaseous SO_2 cannot completely account for this measured variability in the millimeter-wave emission of Venus. Thus, it is necessary to study the effect of gaseous H_2SO_4 on the millimeter-wave emission of Venus. This requires knowledge of the MMW opacity of gaseous H_2SO_4 which unfortunately has never been determined for Venus like conditions.

We have measured the opacity of gaseous H_2SO_4 in a CO_2 atmosphere at 550, 570 and 590 K, at 1 and 2 atm total pressure, and at frequency of 94.1 GHz. Our results, in addition to previous centimeter-wavelength results [4] are used to verify a modeling formalism for calculating the expected opacity of this gaseous mixture at other frequencies. This formalism is incorporated into a radiative transfer model to study the effect of gaseous H_2SO_4 on the millimeter wavelength (MMW) emission of Venus.

Experimental Configuration:

The experimental setup used to measure the MMW opacity of gaseous H_2SO_4 in CO_2 atmosphere consists of a free space transmission system as shown in Figure 1. In this system, a glass cell contains the H_2SO_4/CO_2 gaseous mixture which is introduced prior to the measurement process. The glass cell is located inside a temperature-controlled chamber. A transmitting antenna is used to launch energy into the glass chamber. A receiving antenna is placed at the output of the glass cell in order to collect the outgoing signal. Using a precision variable attenuator, the resulting opacity of the gaseous mixture is measured.

Measurement Results:

The measured absorptivity (dB/km) of H_2SO_4/CO_2 at 94.1 GHz is shown in Figure 2 where it is plotted as a function of temperature for 2 and 1 atm. The reported absorptivities in Figure 2 are normalized to their respective mixing ratios. The measurements were performed at 550, 570, and 590 K in order to allow enough H_2SO_4 vapor pressure in the glass cell.

Although the measurements were performed at 94.1 GHz, care must be taken when projecting the absorption of H_2SO_4 at frequencies far from 94.1 GHz. As a result, we have developed an absorption model based on a Van Vleck-Weisskopf (VVW) formalism. In this formalism, we added the contributions from 2359 resonant lines of sulfuric acid computed by Pickett et al. (private communication, 1991) which cover frequencies between 1.5 and 450 GHz.

In order to fully implement the VVW formalism, an appropriate broadening parameter must be determined. To solve this problem, we adjusted the broadening parameter so that the calculated opacity matches the measured absorptivity at 94.1 GHz and the microwave opacities at 2.24 and 8.42 GHz reported by Steffes [4]. Comparisons between the calculated and measured opacity of H_2SO_4/CO_2 are shown in Figures 2,3, and 4. A careful examination of these results indicates that the calculated opacities of H_2SO_4 using the VVW formalism with a broadening parameter of 1.55 MHz/Torr agree well with the measured microwave and millimeter-wave opacities of the gaseous mixture. This finding is quite important since it demonstrates for the first time that the VVW formalism can be used to accurately predict the opacity of H_2SO_4/CO_2 gaseous mixture over a wide frequency range.

Modeling of the Atmosphere of Venus:

A radiative transfer model has been developed in order to investigate the effects of the atmospheric constituents of Venus on its MMW emission. Such constituents include gaseous SO_2, liquid sulfuric acid (cloud condensates), and gaseous H_2SO_4.

a) Sensitivity to Liquid H_2SO_4:

Results from the radiative transfer model indicate that liquid H_2SO_4 does indeed affect the brightness temperature of Venus at millimeter wavelengths [3]. For instance, at 112 GHz a decrease in brightness temperature of 2 K is obtained for a uniform cloud layer between 48-50 km where droplets sizes of 25 micron and a bulk density of 50 mg/m^3 are assumed. However, this decrease in brightness temperature is much less than the reported variation in the emission of Venus which indicates that variations in the abundance of liquid H_2SO_4 are not the major source of the observed brightness temperature variation.

b) Sensitivity to SO_2:

The effects of gaseous SO_2 on the computed MMW emission of Venus are well described in Fahd & Steffes [2]. Using an abundance profile of 62 ppm below an altitude of 48 km, we have found that the brightness temperature is decreased by approximately 5 K. Although this decrease is significant, it cannot completely account for the measured variation in emission.

c) Sensitivity to Gaseous H_2SO_4:

Using the developed model for the absorption of gaseous H_2SO_4 in a CO_2 atmosphere, we have found that this gaseous mixture seem to have the biggest effect on the calculated brightness temperature of Venus. Specifically at 112 GHz, a drop of 14 K is observed assuming an H_2SO_4(g) abundance of 25 ppm between 48 and 38 km. This decrease in brightness temperature is quite significant compared with the effects of gaseous SO_2 and liquid H_2SO_4. Thus, we can state that the variations observed by de Pater et al. [1] are most likely due to the variations in the abundance of gaseous sulfuric acid and not to liquid sulfuric acid or gaseous sulfur dioxide as previously suggested.

A plot of the calculated millimeter-wave spectrum of Venus based on the presence of one or more constituents is shown in Figure 5. The results reported in this figure show the effect that H_2SO_4 (g) has on the MMW spectrum of Venus. In addition, the results show that there are specific millimeter-wave frequencies which are especially sensitive to the abundance of H_2SO_4 vapor in the lower atmosphere of Venus.

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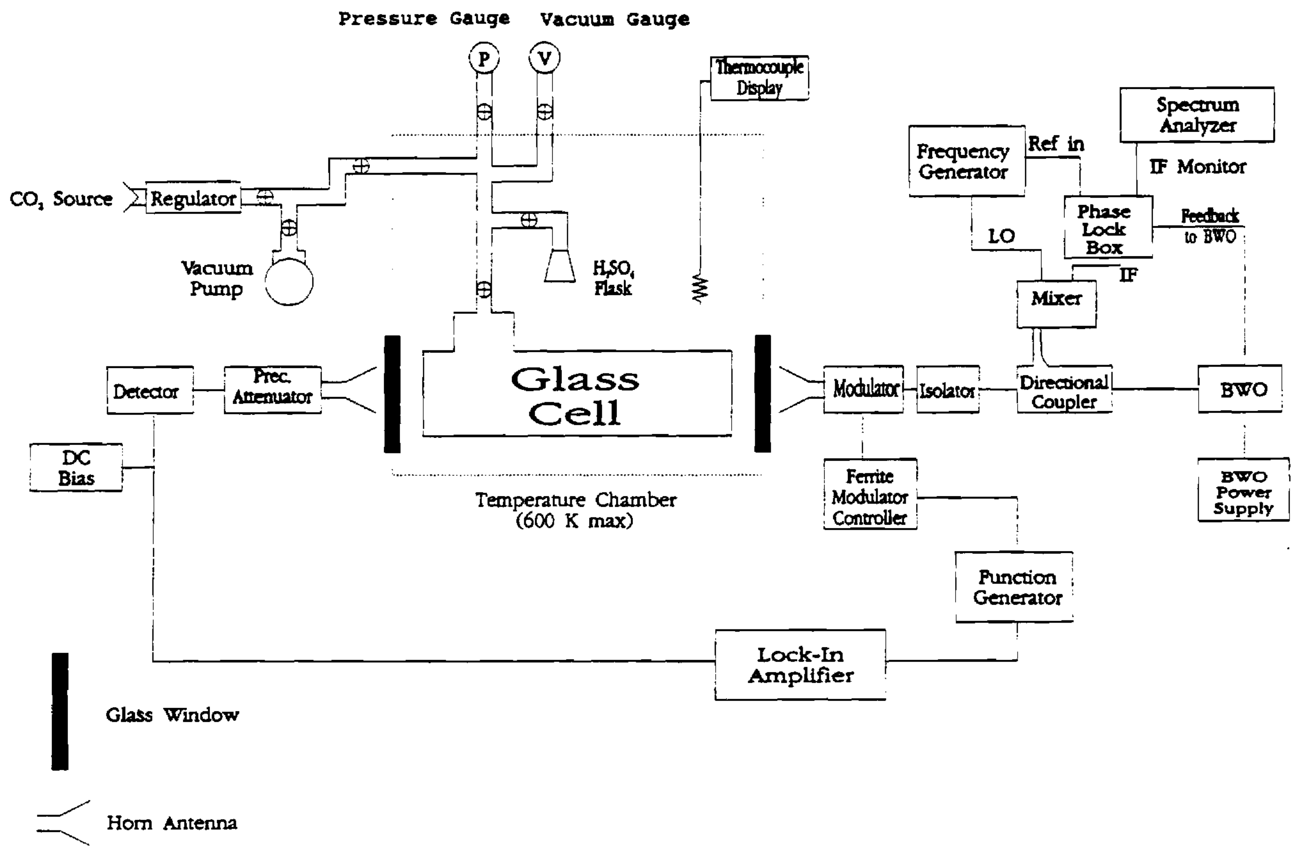
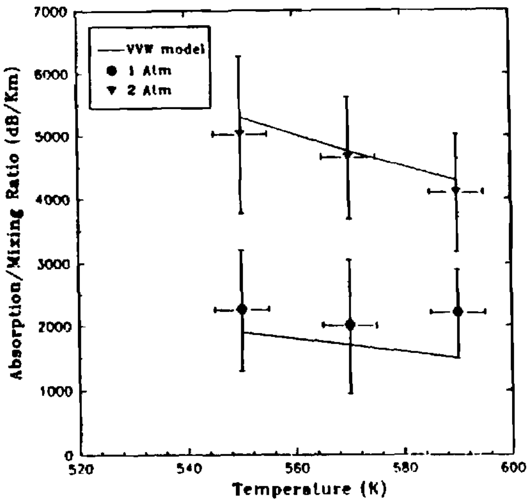


Figure 1 Block diagram of the atmospheric simulator as configured for measurements of the millimeter-wave absorption at 94.1 GHz.



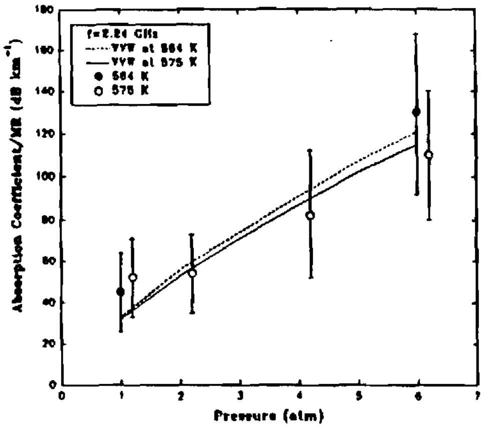
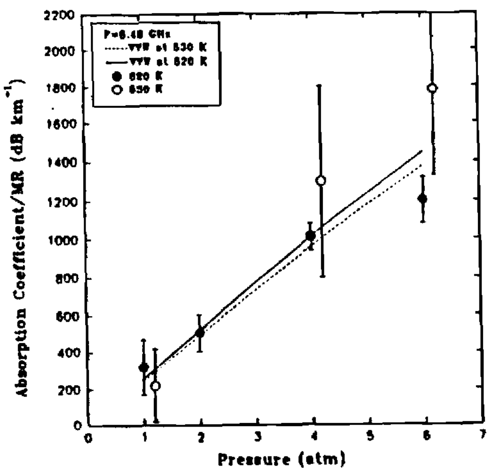


Figure 2 Laboratory measurements of the normalized absorptivity (dB/km) of gaseous H_2SO_4 in a CO_2 atmosphere at 94.1 GHz. Solid curves are the theoretically calculated absorption from the VVW formalism.

Figure 3 Comparison between the measured absorption (normalized by mixing ratio) of H_2SO_4 (Steffes, 1985) and the calculated absorption from the VVW formalism at 2.24 GHz.



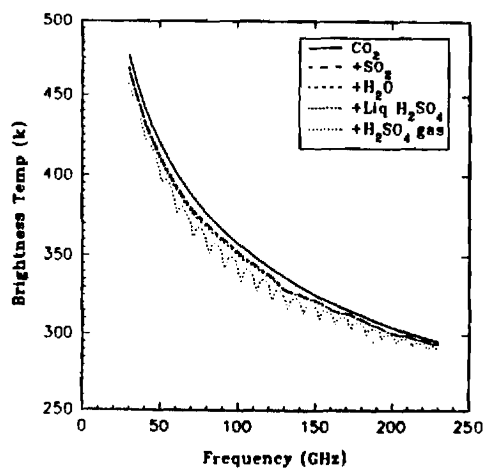


Figure 4 Comparison between the measured absorption (normalized by mixing ratio) of H_2SO_4 (Steffes, 1985) and the calculated absorption from the VVW formalism at 8.42 GHz.

Figure 5 Comparison of the effects of atmospheric constituents on the brightness temperature of Venus between 30 and 230 GHz.

PRELIMINARY RESULTS FROM LABORATORY MEASUREMENTS OF THE CENTIMETER WAVELENGTH OPACITY OF HYDROGEN SULFIDE (H_2S) UNDER SIMULATED CONDITIONS FOR THE OUTER PLANETS

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Because of the large abundance of ammonia in Jupiter's atmosphere, it has not been possible to detect either the microwave or millimeter-wavelength opacities from the gaseous H_2S thought to exist deep in that atmosphere. (See, for example, Joiner et al., 1992, IEEE Trans. on Microwave Theory and Technique 40, June 1992; pp 1101-1109.) However ammonia is substantially depleted in the atmospheres of Uranus and Neptune, and it has been suggested by de Pater et al. (Icarus 91, June 1991, pp 220-233) that the pressure broadened absorption from H_2S significantly affects the centimeter wavelength emission from those planets. In order to accurately infer the abundance and distribution of H_2S in the deep atmospheres of Uranus and Neptune, either from their centimeter radio emission or from radio occultation measurements, accurate laboratory measurements of the microwave opacity from gaseous H_2S under simulated conditions for the outer planets must be conducted at centimeter wavelengths. Such a laboratory measurement program has recently been initiated at Georgia Tech, in which measurements of the opacity of gaseous H_2S in a H_2/He atmosphere are conducted at pressures from 1 to 6 Bars, at temperatures from 173 to 294K, and at frequencies of 2.25, 8.5, and 21.7 GHz. While (to date) measurements have only been conducted at room temperature, our results already indicate that the centimeter wavelength opacity from gaseous H_2S in an H_2/He atmosphere significantly exceeds that which would be predicted using the Van Vleck-Weisskopf formalism, even when the newly measured value for H_2S line broadening (Joiner et al., 1992, Ibid.) is used. Thus alternative lineshape models will be developed to reflect the laboratory results.

** Presented at the Fourth International Conference on Laboratory Research for Planetary Atmospheres, October 10, 1992.

I. EXPERIMENTAL APPROACH

The experimental configuration used to measure the microwave opacity of hydrogen sulfide is the same used by Steffes and Jenkins (1987) for characterizing the absorption of gaseous ammonia (NH_3) under simulated Jovian conditions. The absorptivity is measured by observing the effects of the introduced gas mixture on the Q, or quality factor, of two cavity resonators operating from 2.2 to 21.9 GHz. For this experiment a custom H_2S gas mixture was used. The pre-mixed gas mixture (obtained from Matheson) consisted of 82.71% hydrogen, 9.74% helium, and 7.35% hydrogen sulfide. (This mixing ratio was re-verified by the manufacturer immediately after the test was completed. The uncertainty is two percent of the stated component mixing ratio.) The microwave measurements made were at room temperature, but future measurements will be made at Jovian temperatures.

The planetary atmospheric simulator (shown in Figure 1) consists of a stainless steel pressure vessel in which the two cavity resonators are placed. The pressure vessel is connected via stainless steel tubing and valves to a oil diffusion vacuum pump, the tank containing the hydrogen sulfide gas mixture, and separate tanks of helium and hydrogen. The procedure for adding the gas and making microwave measurements is as follows. The valves to the gas tanks are closed and the oil diffusion pump is turned on. The pressure inside the vessel is monitored via a thermocouple vacuum gauge that is able to measure pressures between 0 and 800 Torr. When the pressure inside the vessel has reached 3 Torr or less, the pump intake valve is closed and the pump is turned off. At this point the vessel is essentially at a vacuum and measurements of the Q are taken. Additional measurements of the Q are made when a mixture of only hydrogen and helium are present. Finally, the Q is measured with the test mixture.

Included in the microwave subsystem are two cavity resonators. The large cavity resonator is operated from 2.2 to 2.3 GHz and from 8.4 to 8.7 GHz. The large cavity resonator is coupled via RG-142B coaxial cable in separate sections. The first section is located inside the pressure vessel. The RG-142B connects from the cavity itself (two ports, one for exciting the cavity and one for extracting the signal) to female-to-female type N hermetically sealed connectors (two) which feed through the pressure vessel's top stainless steel flange. UG-88/U BNC connnectors are used with the coaxial cable. The second section is outside of the pressure vessel. RG-142B is connected from the female type N connectors (two) on the outside of the flange to a microwave source and to a high resolution spectrum analyzer. The small cavity resonator is operated from 21.4 to 21.9 GHz. The small resonator has the same configuration as the large resonator except that semi-rigid cables with SMA connectors are used and female-to- female SMA hermetically sealed connectors feed through the top flange.

The microwave oscillators used were the HP 8690 A & B sweep oscillators. A 10 db attenuator is connected at the output of each oscillator to reduce the effect of variations in the coupling to the cavity resonator. These changes in coupling, which we refer to as dielectric loading, are due to the dielectric constant or permittivity of the gas mixtures and are not related to the absorptivity of the gases. The cable from the output port of the cavity resonator is connected to a high resolution spectrum analyzer. The high resolution spectrum analyzer used was the HP 8562B.

The cavity resonator operates as a bandpass filter. As a result there will be many resonances observed with the spectrum analyzer. The Q of the resonator, which is defined as the ratio of the resonant center frequency to the resonance half-power bandwidth, is proportional to the ratio of energy stored in the resonator to the energy lost per cycle. Minimal coupling is used so as to maximize Q and minimize the variations in Q that might result from changes in coupling that could occur when gases are introduced into the resonator. The resonances selected for measurement were at 2.25, 8.52, and 21.7 GHz. (Frequencies apply when the system is at atmospheric pressure and room temperature.) These resonances were chosen on the basis of their sharpness and symmetry.

The following measurements were made at each resonance: the center frequency, the signal level of the center frequency (S- resonator), the half power bandwidth, the signal level of the source (S-source is obtained by connecting the signal and excited port cables at the outside flange connectors directly together thereby by-passing the signal path through the resonator), and estimating the effect of noise on each measurement. Ten data points were obtained for each measurement above. Note that when any gas is added to or removed from the pressure vessel, the 8.5 GHz resonance is tracked on the spectrum analyzer. The frequency shift in the resonance is due the dielectric properties of the gas loading the system. Therefore it is important to always add gas slowly so as to track this shift in frequency. The reason for tracking the 8.5 GHz line is due to the close proximity of other resonances which may cause confusion in identifying the original resonance.

With the system at a vacuum, the measurements were taken and the mean computed for the data. The resulting values are given in Table One. At this point helium was added to bring the pressure to 9 psi and hydrogen was added to bring the total pressure to 76 psig (6 atmospheres). This mixture was used to evaluate the effect of dielectric loading on the system. The measurements were collected and the mean computed for the data. The results are given in Table Two. The hydrogen - helium gas mixture was then vented from the pressure vessel.

The diffusion pump was started and left on until the pressure inside the vessel was reduced to below 3 Torr.

The hydrogen - hydrogen sulfide - helium gas mixture was next added to bring the total pressure inside the vessel to 76 psig (6 atmospheres). The measurements were collected and the mean computed for the data. The results are given in Table Three. The gas mixture was then vented to reduce the pressure to 3 atmospheres. At this pressure, no opacity was detected. Finally, the pressure vessel was again evacuated. The measurments were collected and compared to the vacuum measurements obtained in Table One. This was done in order to ensure that variations hadn't occurred in the system from the time of the first measurements.

II. EXPERIMENTAL RESULTS

The following results represent the mean values of ten sampled data points collected for each measured quantity at the given gas mixture pressure.

TABLE ONE

Vacuum (3 Torr)

Frequency (GHz)	Bandwidth (KHz)	S-resonator (dBm)	S-source (dBm)
2.255	28.791	-83.121	-54.621
8.531	78.13	-73.223	-44.182
21.717	1262.9	-40.85	-29.007

Table Two

6 Atmospheres(76 psi) of H_2-He

Frequency (GHz)	Bandwidth (KHz)	S-resonator (dBm)	S-source (dBm)
2.253	30.900	-83.529	-54.403

8.525	78.250	-76.503	-43.585
21.701	1183.3	-42.04	-28.680

Table Three

6 Atmospheres(76 psi) of H_2-He-H_2S

Frequency	Bandwidth	S-resonator	S-source
(GHz)	(KHz)	(dBm)	(dBm)
2.251	32.775	-80.842	-55.134
8.518	85.990	-71.583	-44.584
21.683	1182.7	-42.901	-29.062

For a relatively low-loss gas mixtures, the relation between the absorptivity of the gas mixture and its effects on the Q of a resonance is given by:

$$\alpha = 8.686\,(Q_L^{-1} - Q_C^{-1})\,\pi/\lambda \qquad \textbf{(1)}$$

where α is the absorptivity of the gas mixture in dB/km, Q_L is the quality factor of the cavity resonator when the gas mixture is present, Q_C is the quality factor of the cavity resonator in a vacuum, and λ is the wavelength in km. However, to account for dielectric loading one can use the equation:

$$\alpha = 8.686\,(Q_L^{-1} - Q_{g'}^{-1})\,\pi/\lambda \qquad \textbf{(2)}$$

where Q_L is the quality factor of the lossy gas mixture, $Q_{g'}$ is the quality factor of the same density mixture <u>without</u> the lossy gas, α is the absorptivity of the gas mixture in dB/km, and λ is the wavelength in km. Using this equation and the data in Tables Two and Three the absorptivites are:

$f = 2.25$ GHz $\alpha = .173$ dB/km

$f = 8.52$ GHz $\alpha = .710$ dB/km

$f = 21.7$ GHz $\alpha =$ not detectable

These results are plotted in Figure 2 , along with the expected opacity from this gas mixture computed using the Van Vleck-Weisskopf formalism. (See Joiner et al., 1992.)

III. EXPERIMENTAL UNCERTAINTIES

Experimental uncertainties in the measurement of the absorptivity coefficients of the gaseous mixture can be divided into two major categories: uncertainties due to noise and instrumental uncertainties. In the case of instrumental uncertainties, most of the uncertainties stem from the accuracy of the equipment that measures the bandwidth of the resonance (δf). Additional instrumental uncertainties include the measurement accuracy of f_0 and of t. For the cases of bandwidth, center frequency, and transmissivity measurement, an accuracy of 5% was achieved and is included in the error bars in Figure 2 and Table Four.

Additional instrumental uncertainties result from asymmetry of the resonances, uncertainties in the measured total pressure, temperature uncertainties, and uncertainties in the mixing ratio. In the case of resonance asymmetry (resonance asymmetry results from the interference of neighboring resonances with the desired resonance), we have found that the absorption coefficients at 2.24 GHz are not greatly affected by the asymmetry effect. In contrast, the asymmetry analysis seems to affect some of the results at 21.7 GHz and the resulting additional uncertainties have been added to the error bars.

In the case of pressure measurement, the accuracy was limited by the equality of the pressure gauge used in the experiment which had a 0.2 atm accuracy throughout its usable range. The mixing ratio uncertainty is two percent of the stated component mixing ratio.

The uncertainties from noise in the system are primarily due to the large insertion loss of the cavities used in the system (required to keep the quality factor high). To account for noise uncertainties, repeated measurements were conducted at each particular pressure. As a result, statistics were developed to account for the variations of Q, t, and δf which were subsequently used to develop 1-σ error bars for the absorption coefficient of the H_2S gas mixture.

CONCLUSION

The results obtained from this experiment show that in a 6 atm hydrogen/helium atmosphere, hydrogen sulfide is more opaque at centimeter wavelengths than predicted by Van-Vleck Weisskopf theory. The noted variation from Van Vleck-Weisskopf theory parallels variations from that theory for both NH_3 (Joiner and Steffes, 1991) and for SO_2 (Fahd and Steffes, 1992) in that it is more pronounced at the wavelengths farthest from the line centers, i.e., at lower frequencies. Further measurements are needed with hydrogen sulfide in order to explain the discrepancies. Likewise, work with H_2S at colder temperatures is needed to characterize its effect on the centimeter wavelength emission spectra of Uranus and Neptune.

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Steffes, P.G. and J.M. Jenkins (1987). Laboratory measurements of the microwave opacity of gaseous ammonia (NH_3) under simulated conditions for the Jovian atmosphere. Icarus 72, 35-47.

TABLE FOUR

ABSORPTIVITY OF H_2S AT THREE MICROWAVE FREQUENCIES

Frequency (GHz)	Measured Absorption α (dB/km)	Measurement Error (dB/km) $\pm 1\sigma_\alpha$	VVW Prediction (dB/km)
2.25	0.171	±0.047	0.01
8.50	0.704	±0.164	0.14
21.7	< 4.00	----	0.90

NOTE: Pressure = 6.1 atmospheres Temperature = 22C +/- 2C
Mixture = 82.71% H_2, 9.74% He, 7.55% H_2S

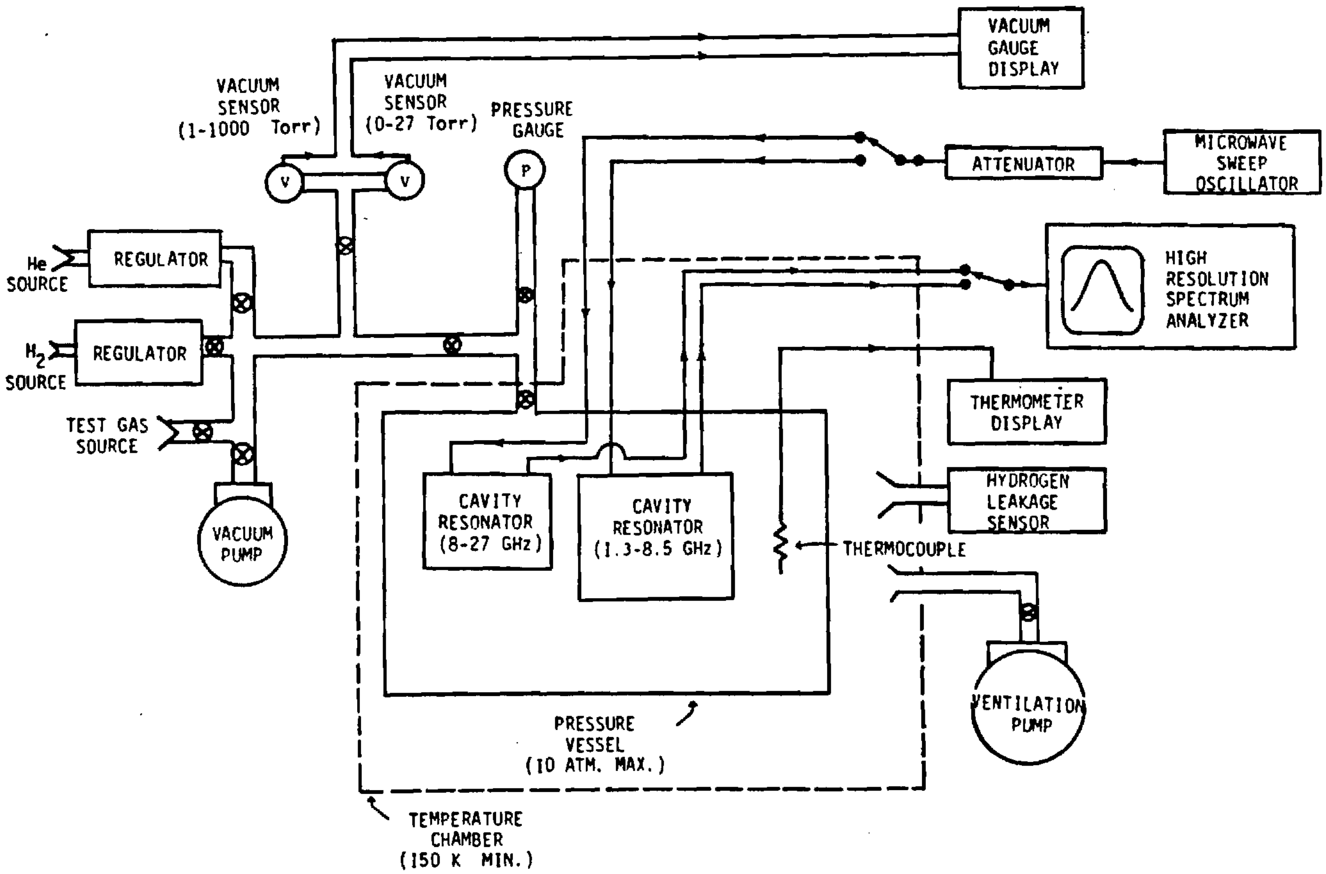
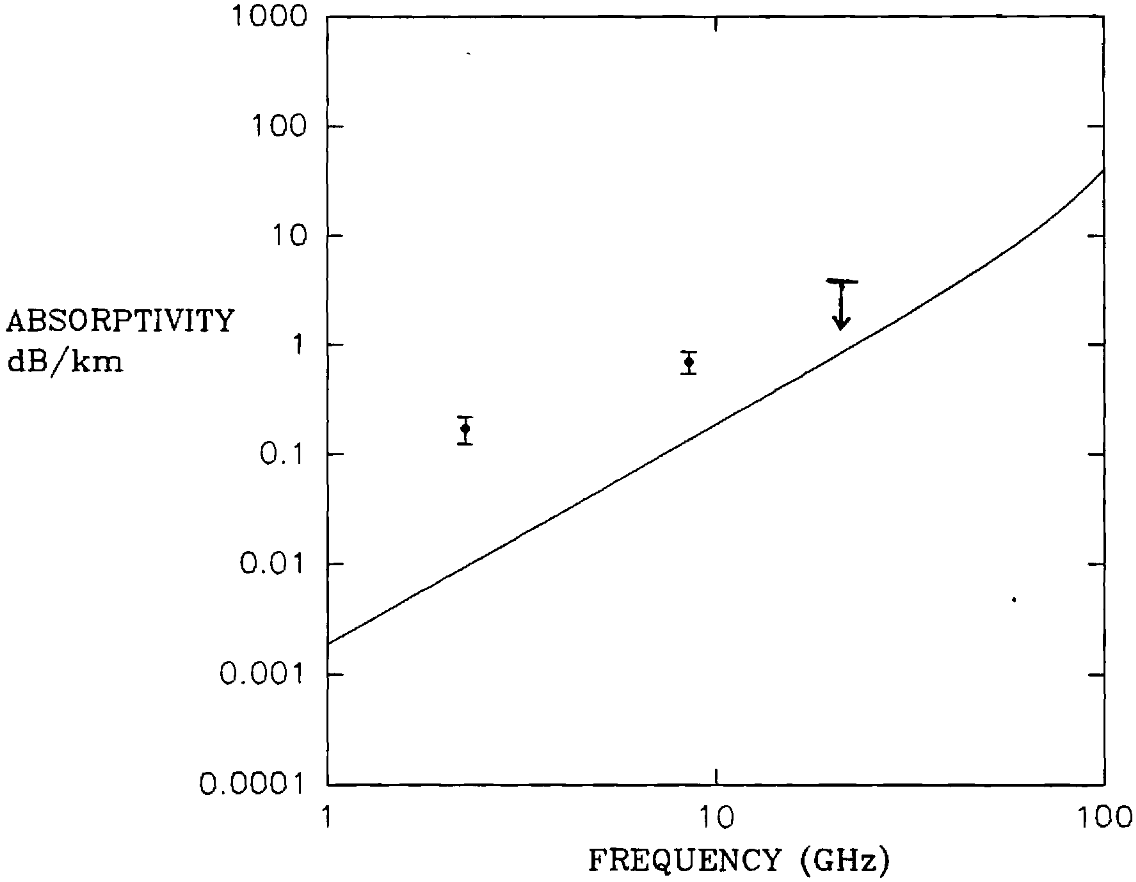


Figure 1: Block diagram of atmospheric simulator as configured for measurement of the microwave opacity from H_2S under simulated outer planets conditions

FIGURE 2:

COMPARISON OF EXPERIMENTAL VERSUS VVW PREDICTION FOR HYDROGEN SULFIDE ABSORPTIVITY



PRESSURE = 6.1 ATM TEMPERATURE = 295K
MIXTURE = 82.71% HYDROGEN
9.74% HELIUM
7.55% HYDROGEN SULFIDE

APPENDIX C:

DIVISION FOR PLANETARY SCIENCES ABSTRACT FORM

Preliminary Results from the October 1991 Magellan Radio Occultation Experiment

P.G. Steffes (Georgia Inst. of Technology), J.M. Jenkins (SETI Institute/NASA-Ames R.C.), G.L. Tyler, J. Twicken (Stanford Univ.), R.S. Austin, and S.W. Asmar (JPL/CalTech)

On October 5 and 6, 1991, dual-frequency radio occultation measurements of the polar Venus atmosphere were conducted on three successive orbits using the telecommunications system aboard the Magellan spacecraft and the 70 meter DSN antenna at Tidbinbilla, Australia. The high radiated power (EIRP) from the spacecraft, plus the accurate positioning of the spacecraft antenna, has made it possible to develop highly accurate profiles of atmospheric refractivity and absorptivity down to the 36 km level at 3.6 cm, and down to the 34 km level at 13 cm. A polarimetric measurement was also conducted at the 3.6 cm wavelength in an attempt to detect any effects of clouds or lightning on the polarization of the transmitted wave.

No depolarization events have been detected, but preliminary profiles of atmospheric absorptivity provide accurate profiles of absorbing constituent abundances, especially for gaseous H_2SO_4.

Abstract Submitted for the Division for Planetary Sciences Munich Meeting

Date Submitted ____________ Form Version 2/92

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Yes ☐ No ☐ Maybe ☐

DPS Category No. ______ (From list on separate page)

Abstracts must conform to the AAS style as described on the back of this form. Abstract original must be typed or glued directly onto this form. The charge for publication of this abstract in the *Bulletin of the American Astronomical Society* will be included in the registration fee for this meeting.

Deadline for receipt of abstract: July 13, 1992

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Figure 1-1

ATMOSPHERIC RADIO OCCULTATION MEASUREMENTS WITH MAGELLAN AT VENUS

5 OCTOBER 91 - 6 OCTOBER 91

GOALS: OBTAIN REFRACTIVITY AND ABSORPTIVITY PROFILES OF VENUS ATMOSPHERE TO LOWEST POSSIBLE ALTITUDES..

CONDUCT EXPERIMENT AT TWO FREQUENCIES: 2298 MHz (13 cm)
8425 MHz (3.6 cm)
SO AS TO ACHIEVE HIGHER ACCURACY....

USE ABSORPTIVITY PROFILES TO CHARACTERIZE ABUNDANCE AND DISTRIBUTION OF GASEOUS H_2SO_4 AND IDENTIFY SPATIAL AND TEMPORAL VARIATIONS OF SAME.

DEVELOP T-P PROFILES FROM REFRACTIVITY PROFILES AND CORRELATE VARIATIONS WITH VARIATIONS IN H_2SO_4 ABUNDANCE, AND WITH MAPS MADE BY GALILEO NIMS.

ADVANTAGES OVER PREVIOUS RADIO OCCULTATION EXPERIMENTS:

MUCH HIGHER EIRP (EFFECTIVE ISOTROPIC RADIATED POWER) FROM MAGELLAN RESULTS IN PROFILES WITH SMALLER ERROR BARS AND ALLOWS PROBING MUCH DEEPER INTO THE ATMOSPHERE. AS A COMPARISON WITH PREVIOUS PIONEER-VENUS RESULTS:

	PIONEER-VENUS	MAGELLAN
DEPTH PROBED AT 13 CM:	39 km	33.8 km
DEPTH PROBED AT 3.6 CM:	52 km	35.6 km
BENDING ANGLE MEASURED (MAXIMUM) AT 13 CM:	8 degrees	15.5 degrees
BENDING ANGLE MEASURED (MAXIMUM) AT 3.6 CM:	1.5 degrees	11.0 degrees

CHALLENGES:

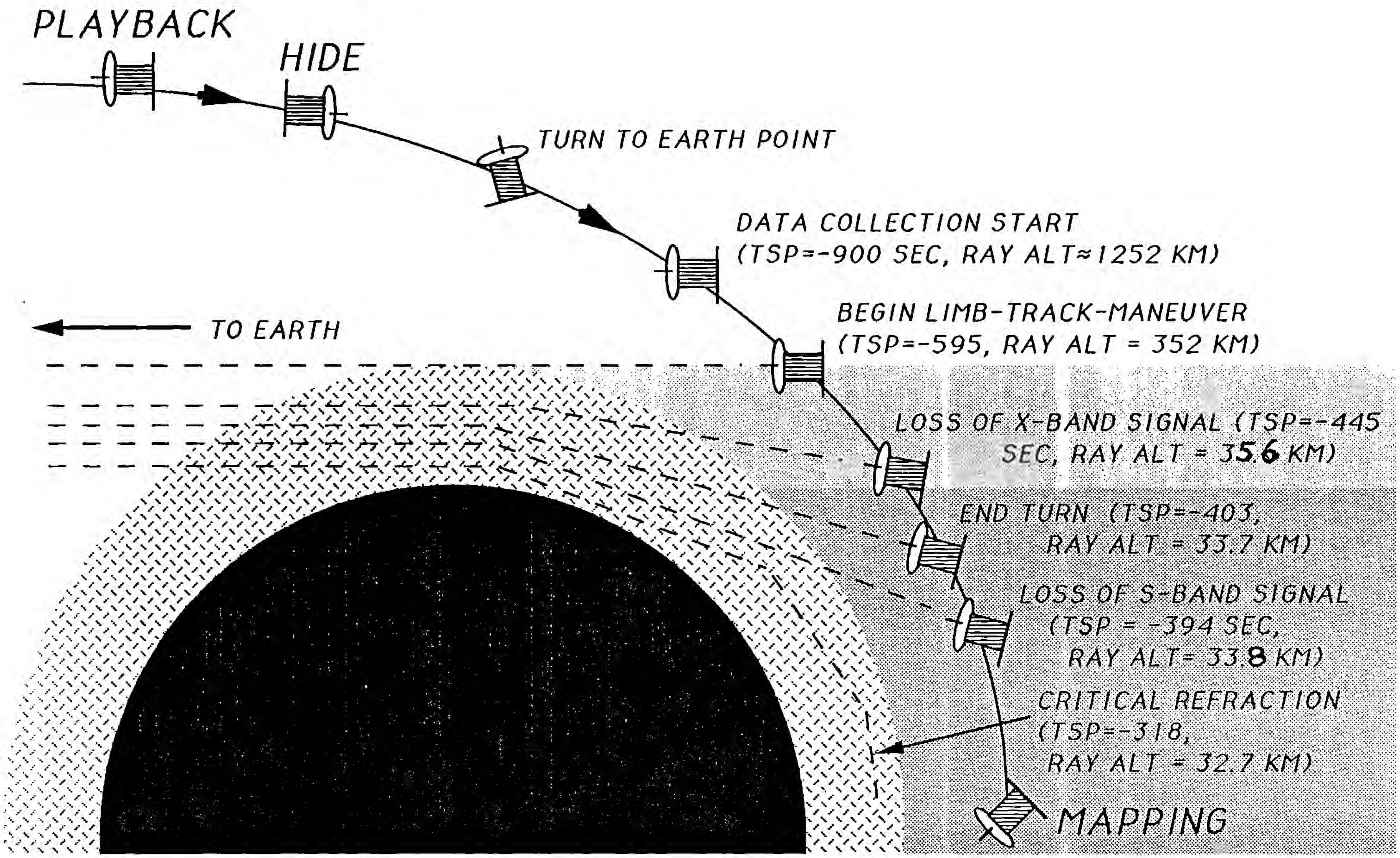
REQUIRED DEVELOPMENT OF SPECIAL SPACECRAFT TRACKING MANEUVER SO AS TO KEEP SPACECRAFT HIGH-GAIN ANTENNA POINTED TOWARD THE LIMB OF THE PLANET (AND THUS THE RAY PATH BACK TO EARTH).

SPECIAL OPERATION OF 70-METER GROUND STATION (DSS-43)

5 OCTOBER RADIOSCIENCE EXPERIMENT PROFILE

Figure-1-2

- Measure abundance of H_2SO_4 by determining atmospheric absorptivity (signal attenuation) and refractivity (signal doppler shift) during occultation.



REGION PROBED BY MAGELLAN RADIO OCCULTATION
EXPERIMENT (ORBIT #3212)

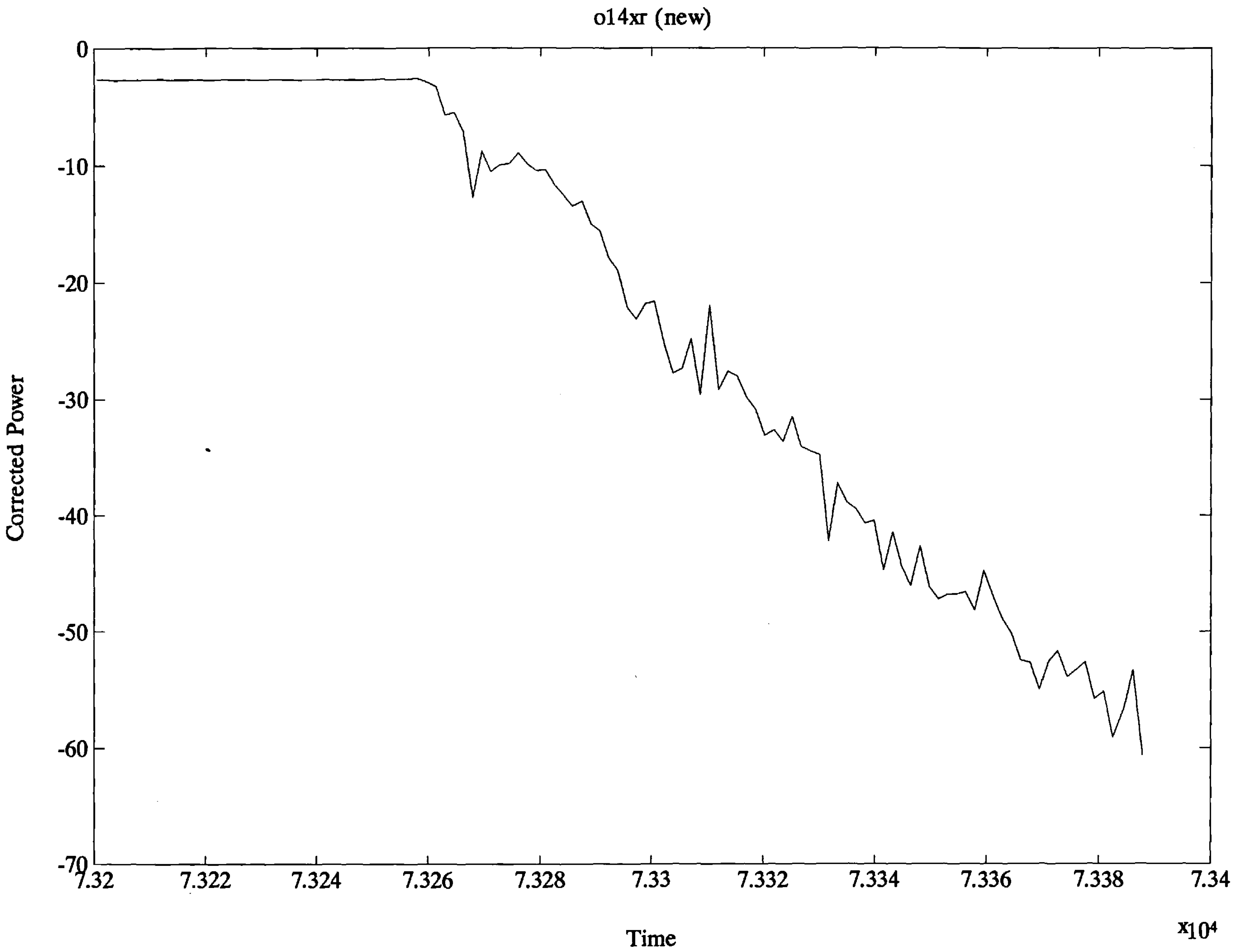
LATITUDE: 61 - 69 degrees North

LONGITUDE: 85 - 93 degrees East (Just West of the Tethus Regio)

SOLAR ZENITH ANGLE: 107-112 degrees (Night side, near terminator)

FIGURE 2

Figure 3-1: Strength of 8425 MHz signal (3.6 cm) during Occultation Experiment



C5

Figure 3-2: Stength of 2298 MHz signal (13 cm) during Occultation Experiment

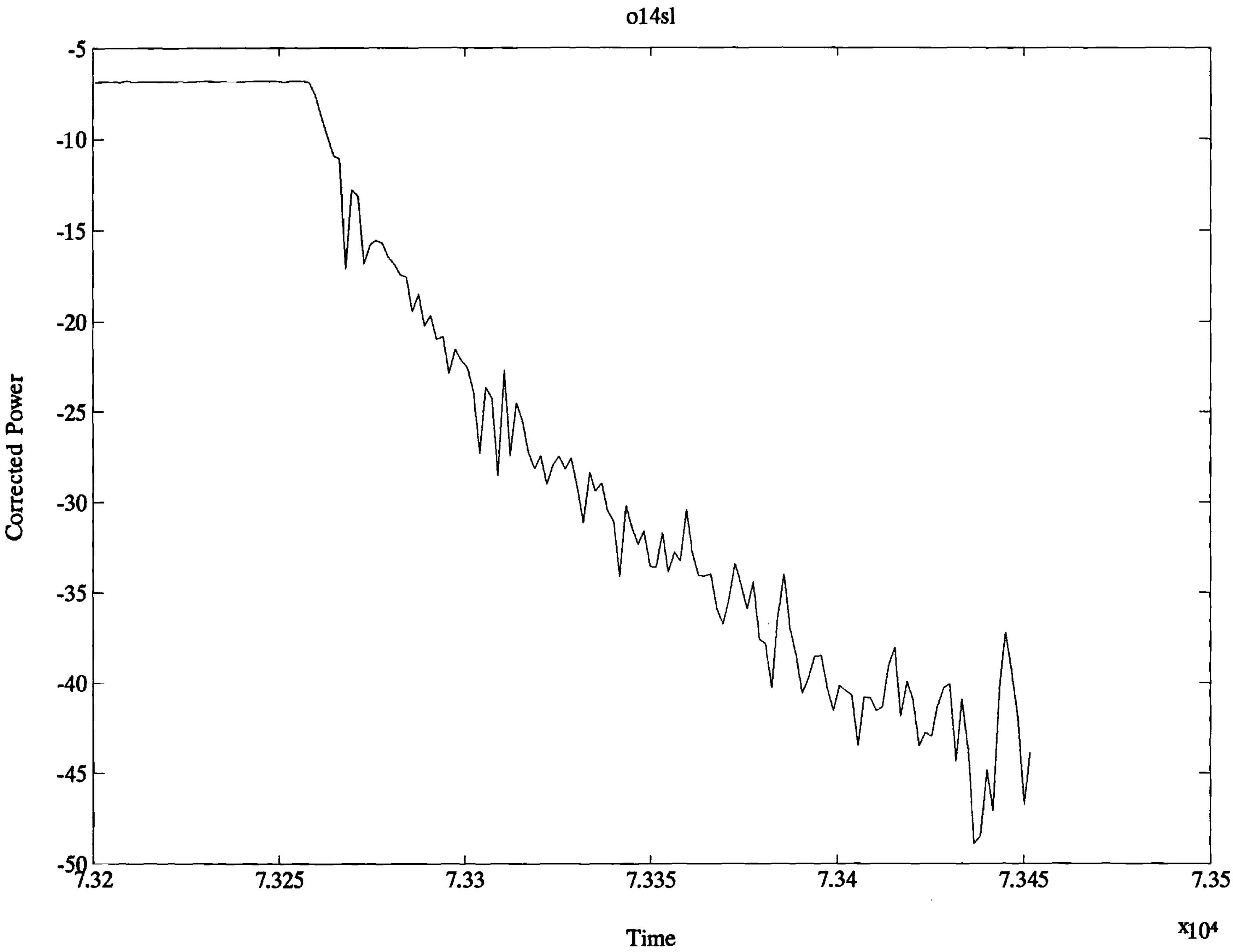


Figure 4-1: Bending of 3.6 cm signal during occultation experiment

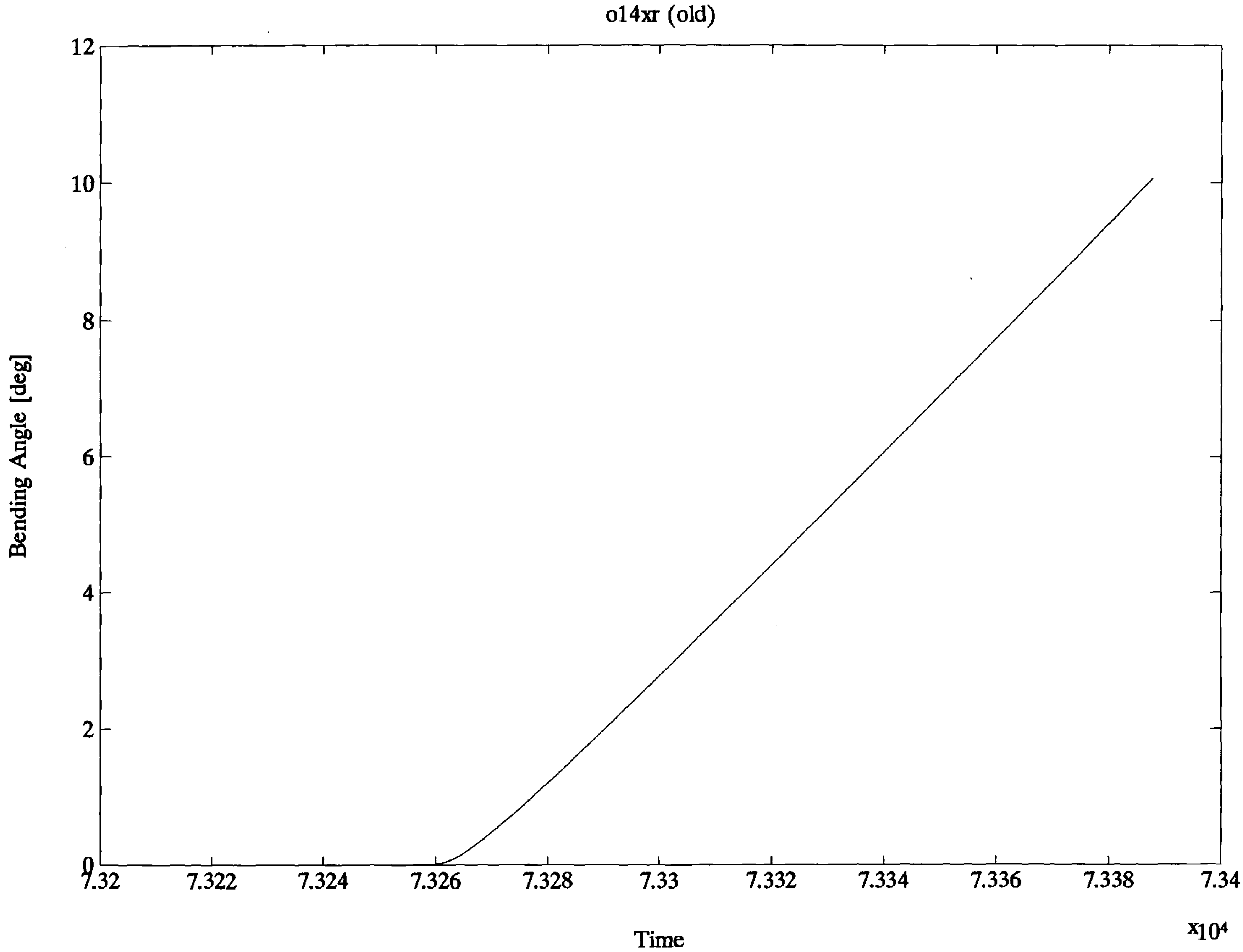


Figure 4-2: Bending of 13 cm signal during occultation experiment

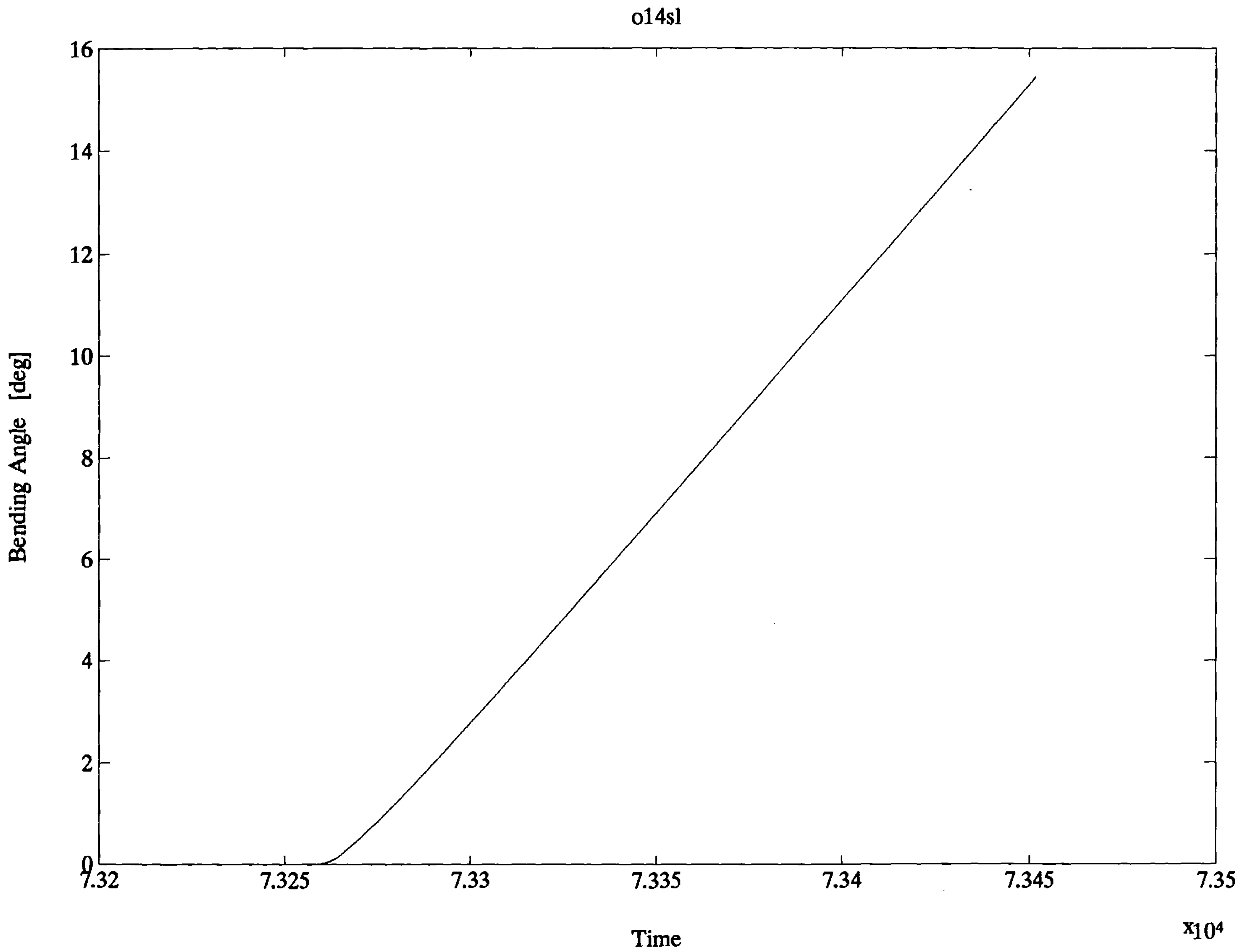
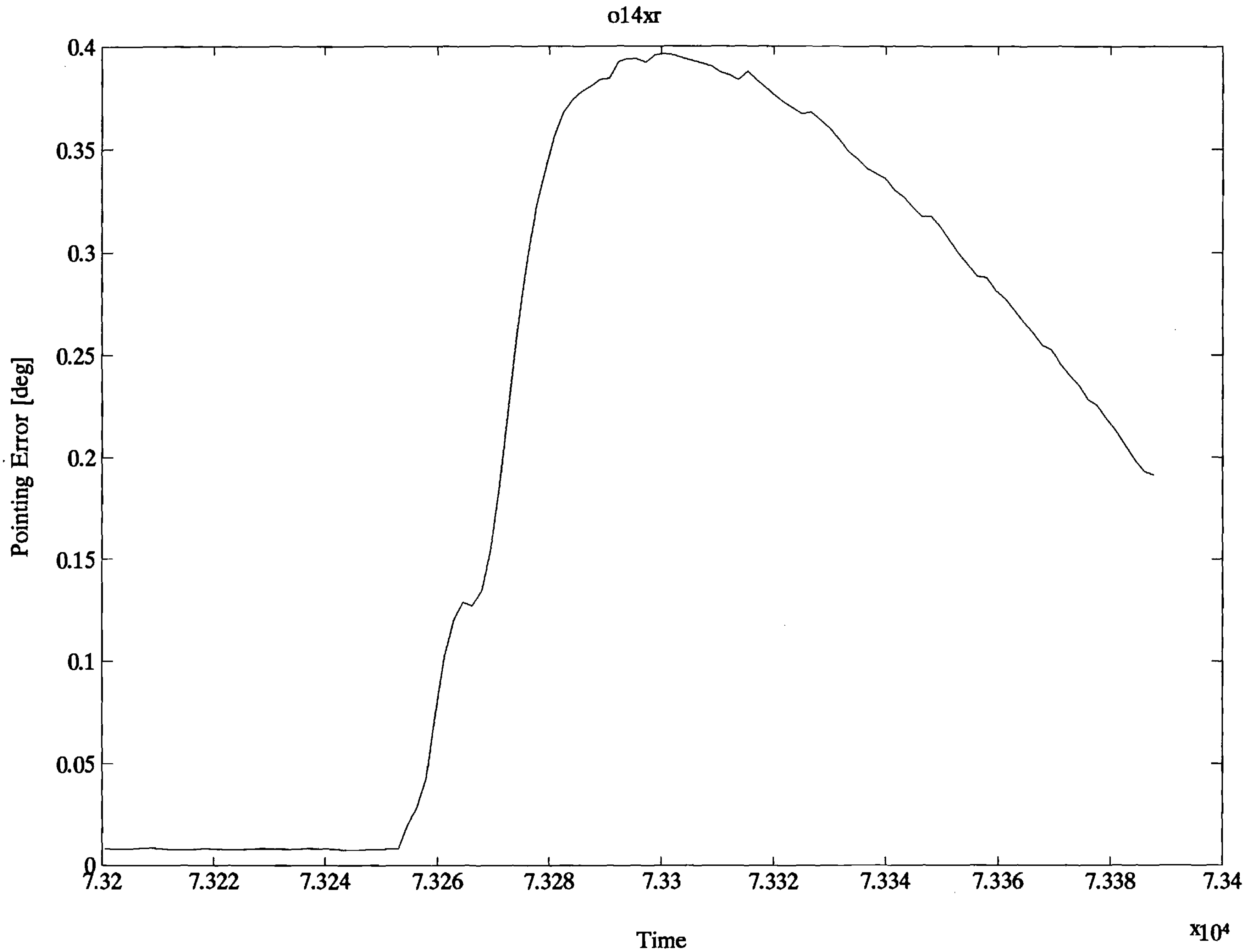


Figure 5: Accuracy of antenna pointing maneuver relative to actual ray bending



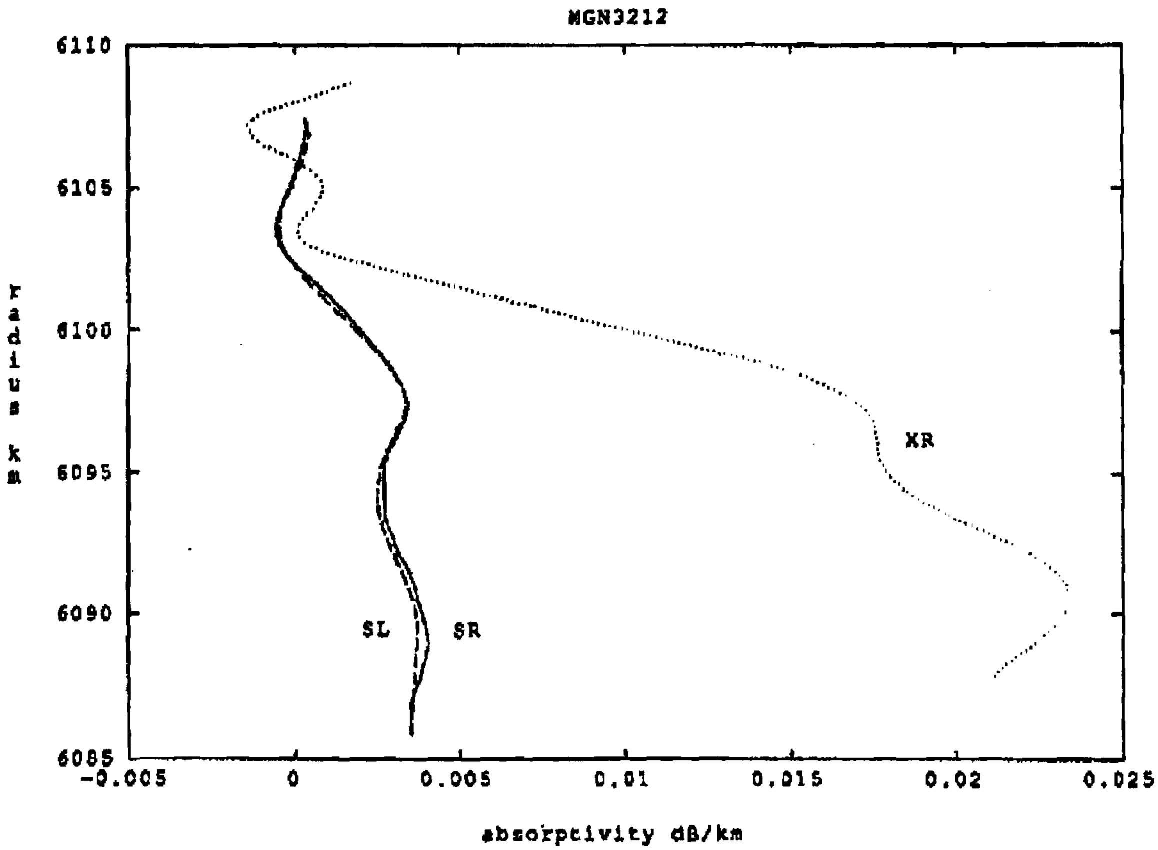

MGN3212
6110
6105
6100
6095
6090
6085
-0.005
0
0.005
0.01
0.015
0.02
0.025
radius km
absorptivity dB/km
XR
SL
SR

Figure 6-1

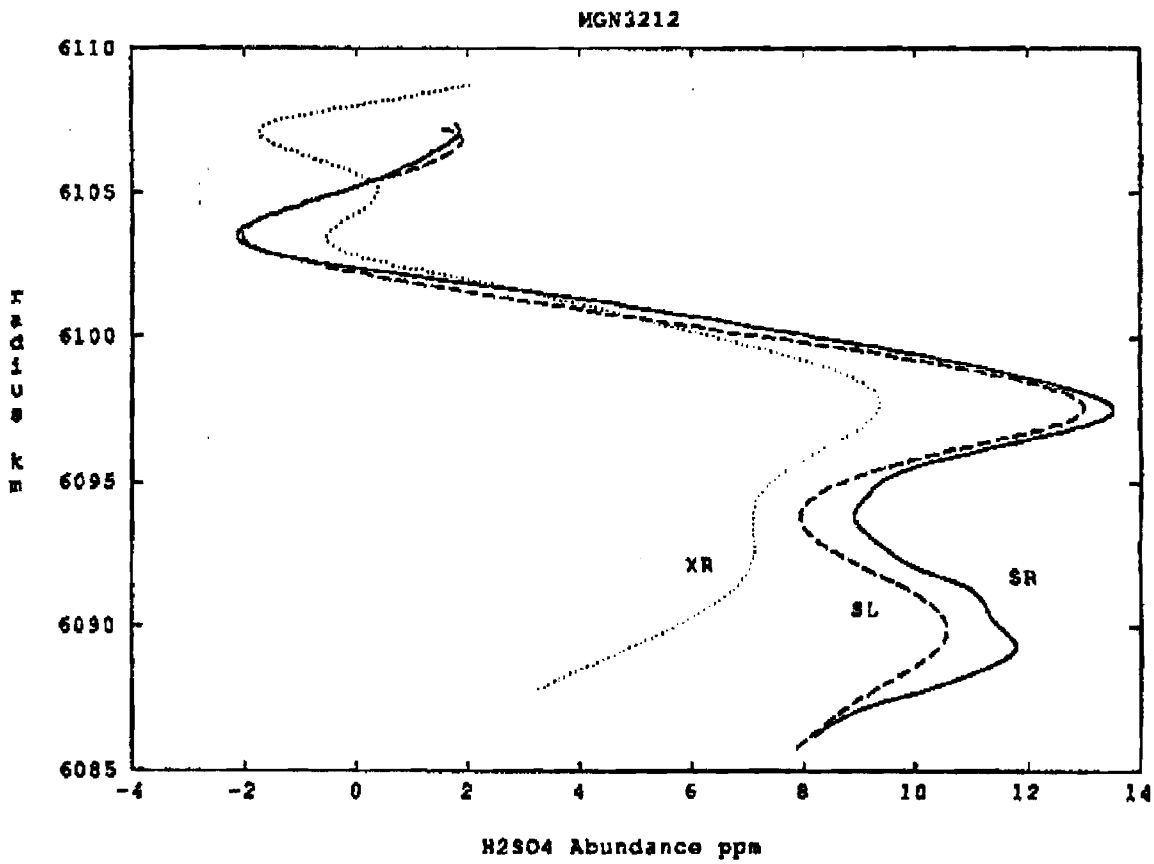

MGN3212
6110
6105
6100
6095
6090
6085
radius km
-4
-2
0
2
4
6
8
10
12
14
H2SO4 Abundance ppm
XR
SL
SR

Figure 6-2

Contributors to the Magellan
Radio Occultation Experiment

<u>Georgia Institute of Technology</u>:

* Paul G. Steffes
* Jon M. Jenkins (now with SETI Institute/NASA Ames Research Center)

<u>Jet Propulsion Laboratory</u>

* Sami W. Asmar
* Richard S. Austin
Ann S. Devereaux
Dan Lyons
Thomas W. Thompson

<u>Martin Marietta Corporation</u>

* Eric H. Seale
Julie Webster

<u>Stanford University</u>

* G. Leonard Tyler
Joseph Twicken

* Principals

- Figure 7 -

E21-?
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STATUS REPORT #19
AND RENEWAL PROPOSAL ENTITLED

LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

to the

National Aeronautics and Space Administration
for Grant NAGW-533

Report Period: November 1, 1992 through October 31, 1993

Proposed Renewal Period: November 1, 1993 through October 31, 1994

COVER SHEET

RTOP No. ______
Grant/Contract No. NAGW-533
Date Received ______

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
SOLAR SYSTEM EXPLORATION DIVISION
PLANETARY ATMOSPHERES PROGRAM*

______ **Full Proposal** ____x____ **Progress Report**

TITLE: Laboratory Evaluation and Application of Microwave Absorption Properties under Simulated Conditions for Planetary Atmospheres

TYPE OF ORGANIZATION:** University

RESEARCH AREA*:** Laboratory Measurements: Microwave and Millimeter-wave

DATE SUBMITTED: July 24, 1993

DESIRED STARTING AND ENDING DATES: Annual Renewal: November 1, 1993 - Oct. 31, 199

PRINCIPAL INVESTIGATOR: ______ 7/23/1993
(Signature & Date)

Name: Paul G. Steffes

Title: Associate Professor

Address: School of Electrical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0250

Telephone: (404) 894-3128

AUTHORIZING INSTITUTIONAL OFFICIAL: ______ 7/28/93
(Signature & Date)

Name: Janis L. Goddard

Title: Contracting Officer
Georgia Tech Research Corporation

Address: Centennial Research Building
Georgia Institute of Technology
Atlanta, GA 30332-0420

Telephone: (404) 894-4817

*) Choose one.
**) e.g., profit, nonprofit, university, other educational institutions, etc.
***) Please indicate main research area, such as inner planets; outer planets and satellites; comets; asteroids; planetary detection; theory; laboratory measurements; instrument development; other.

B. COGNIZANT PERSONNEL

For scientific or technical matters relating to the grant (Principal Investigator):

Paul G. Steffes
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0250
Telephone: (404) 894-3128

For contractual and business matters:

Georgia Tech Research Corporation
ATTN: Janis L. Goddard
Georgia Institute of Technology
Atlanta, GA 30332-0250
Telephone: (404) 894-4817

C. PROPOSAL SUMMARY

TITLE: Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres

PRINCIPAL INVESTIGATOR: Paul G. Steffes (Georgia Institute of Technology)

ABSTRACT

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave and millimeter-wave absorbing atmospheric constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements <u>and</u> to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profile of constituents in those planetary atmospheres.

Key accomplishments achieved in the currently completed grant year include:

1. Laboratory measurement of the microwave opacity and refraction from H_2S under simulated conditions for the outer planets (i.e., in an H_2/He atmosphere at temperatures from 193-290 K, and at pressures from 2-6 Bars). Measurements were made at 2.25 GHz (13.3 cm), 8.5 GHz (3.5 cm), and 21.7 GHz (1.4 cm). (Ref., DeBoer and Steffes, 1993a, appended).

2. Measurement of the depolarization and absorption of centimeter waves in the Venus atmosphere using Magellan radio occultations.

3. Refinement of models for the opacity of H_2SO_4(g) in the Venus atmosphere.

Key activities planned for the next grant year include:

1. Application of the results for H_2S to our radiative transfer model so as to estimate limits on its abundance and distribution in the atmospheres of Uranus and Neptune.

2. Laboratory measurement of the temperature dependence of the opacity from SO_2 at 1.3 cm at temperatures from 365 K to 550 K and at pressures from 1-6 Bars in a CO_2 atmosphere.

D. BUDGET SUMMARY

PRINCIPAL INVESTIGATOR: Paul G. Steffes

TITLE: Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres

GRANT NUMBER: NAGW-533
For the period of November 1, 1993 through October 31, 1994

ESTIMATED COST BREAKDOWN

I.	DIRECT SALARIES AND WAGES*:		$40,928
	A. Principal Investigator P.G. Steffes 25% time, calendar year (.25 person-years)	$19,855	
	B. 1 Graduate Student (D.R. DeBoer) 50% time, calendar year (.5 person-years)	$15,000	
	C. 1 Graduate Student (S. Suleiman) 9% time, calendar year (.09 person-years)	$ 2,693	
	D. 1 Research Engineer II (lab support) 7% time, calendar year (.07 person-years)	$ 3,380	
II.	FRINGE BENEFITS**: 25.1% of Direct Salaries & Wages (less students)		$ 5,832
III.	MATERIALS, SUPPLIES, AND SERVICES		$ 1,300
	A. Gases, liquids and supplies for Experiments	$ 700	
	B. Miscellaneous Project Supplies and page charges	$ 600	
IV.	TRAVEL		$ 1,300
	A. Travel for Student to AAS/DPS Meeting (Williamsburg, VA, 6 days duration, airfare $600 plus registration and $100/day)	$ 1,300	
	SUBTOTAL - ESTIMATE OF DIRECT COSTS:		$49,360
V.	OVERHEAD (Indirect Expense)**: 37% of Modified Total Direct Cost Base		$18,264
	TOTAL BUDGET (12 months) REQUESTED FROM NASA:		$67,624

ESTIMATED TOTALS TO COMPLETION OF RESEARCH:
Funds: $135,248 Months: 24

*The salary and wage rates are based on FY 94 salaries for the Georgia Institute of Technology. The Georgia Tech Fiscal Year is July 1 through June 30.
**Rates are estimated for the period July 1, 1993 through June 30, 1994 and are subject to adjustment upon DCAA audit and ONR negotiations.

E. LIST OF CURRENT AND PENDING RESEARCH SUPPORT FOR PRINCIPAL INVESTIGATOR

(Paul G. Steffes)

A. Current Support

1. National Aeronautics and Space Administration - Grant NAGW-533, "Laboratory Evaluation and Application of Microwave Absorption Properties under Simulated Conditions for Planetary Atmospheres," \$67,624 for 12-month period (11/1/92 - 10/31/93). P.I. time commitment: 25% (3 person-months). (THIS PROPOSAL IS FOR RENEWAL OF THIS GRANT.)

2. National Aeronautics and Space Administration, Ames Research Center - Grant NAG2-700, "Search for Extraterrestrial Intelligence/Microwave Observing Project: Sky Survey Team Member," \$72,345 for 12-month period (3/1/93 - 2/28/94). P.I. time commitment: 34% (4 person-months).

B. Pending Support (other than this proposal):

(None)

F. TABLE OF CONTENTS

I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing atmospheric constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or using laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. For example, laboratory measurements conducted in this past year by DeBoer and Steffes (1993a, appended) under Grant NAGW-533, have shown that the opacity from H_2S under simulated conditions for the outer planets is best described by a different lineshape than was previously used in theoretical predictions. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements and to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identify and abundance profiles of constituents in those planetary atmospheres.

II. OUTER PLANETS STUDIES

In this past grant year we have successfully completed laboratory measurements of the microwave opacity and refractivity of gaseous H_2S under simulated conditions for the outer planets (i.e., in an H_2/He atmosphere at temperatures from 193 - 290 K, and at pressures from 2-6 Bars). These measurements were made at 2.25 GHz (13.3 cm), 8.5 GHz (3.5 cm) and 21.7 GHz (1.4 cm), and showed opacity significantly greater than predicted by the Van Vleck-Weisskopf formalism. We will report these results at the Fifth International Conference on Laboratory Research for Planetary Atmospheres (Boulder, CO; October 17, 1993). Our presentation for that conference (DeBoer and Steffes, 1993a) is attached as Appendix A. We are also preparing these results for submission to Icarus or JGR-Planets. Moreover, a more complete method for evaluating the uncertainties which accompany such measurements has been developed (see Appendix B) and will be included in that publication. One additional interesting feature measured was the very high refractivity of H_2S. This may effect the interpretation of Voyager-Neptune radio occultation data.

In the next grant year (November 1, 1993 - October 31, 1994) we expect to complete development of a revised formalism for computing opacity from H_2S under conditions for the outer planets, and to apply that formalism to our radiative transfer models for Uranus and

Neptune. We focus on Uranus and Neptune since they appear to be depleted of NH_3, and thus H_2S may significantly affect the emission from those planets. We will summarize our most recent work to date in this area at the 25th Annual Meeting of the Division for Planetary Sciences/American Astronomical Society to be held in Boulder, Colorado on October 18-22, 1993. (Abstract attached as Appendix C, DeBoer and Steffes 1993b.) While working on developing this formalism, it has occurred to us that many radio astronomers and modelers of atmospheric microwave properties use the GEISA and Poynter-Pickett line catalogs when estimating atmospheric effects. Most do not overtly describe the mechanics of their use of these catalogs which has led to some inconsistencies between various models. As a result, we have developed a "handbook" for the use of the data from these catalogs (Appendix D) which we will publish as an appendix to a future paper.

III. VENUS STUDIES

A. Laboratory Measurements

In the recently completed grant year (November 1, 1992 - October 31, 1993) we have continued to be active in using the Magellan spacecraft to probe the Venus atmosphere by way of radio occultation studies. We have recently completed processing of the October 1991 data, which consisted of three radio occultation measurements at 13 cm (S-Band) and 3.6 cm (X-Band) which probed down to altitudes below 34 km at approximately 57° N latitude and 114° solar zenith angle (early evening). This work has been led by Jon Jenkins (SETI Institute/NASA-Ames) who is supported by the VDAP Program for this activity. The results of the October 1991 experiment is summarized in two papers being prepared for publication. The first (Steffes et al., 1993) describes the nature and conduct of the experiment and is attached as Appendix F. The second (Jenkins et al. , 1993a) actually presents profiles of atmospheric refractivity and absorptivity which are, in turn, used to derive vertical profiles of temperature and gaseous H_2SO_4 (the main microwave absorber) abundance. (A preprint will be forthcoming.) These profiles (with accompanying error bars) will also be presented at the 1993 DPS/AAS Meeting (see Appendix E, Jenkins et al., 1993b).

In addition, 4 more radio occultation measurements were conducted in December 1992 with Magellan at Venus. These are described in Steffes et al. (1993, Appendix F). For none of the experiments so far analyzed have we detected any depolarization.

Using observations of the 1.35 cm Venus brightness, Fahd and Steffes (1992) have estimated an average SO_2 abundance of 62 ppm below the main Venus cloud layer. However, this estimate is uncertain, and one of the major sources of this uncertainty is the temperature dependence of the SO_2 opacity at this wavelength. The temperature dependence is estimated to range between $T^{-3.0}$ and $T^{-4.0}$ depending on frequency and pressure. However, this range of uncertainty would result in a variation of inferred SO_2 abundance from 48 ppm to 70 ppm.

In the next grant year (November 1, 1993 - October 31, 1994) we intend to conduct laboratory measurements of the temperature dependence of 1.38 cm opacity of gaseous SO_2 in a CO_2 atmosphere at pressures from 1 to 6 Bars. Note again that the measurements will be conducted at this frequency (22 GHz) since it is one of the few "windows" in the gaseous H_2SO_4 absorption spectrum which allows measurement of SO_2 at Venus, and because a large number of emission measurements (including, hopefully, VLA maps) will be available at that frequency. The laboratory setup to be used is similar to that described in Fahd and Steffes (1992) except that we use a temperature-regulated commercial oven as the temperature vessel. Also, note that a pre-mixed, constituent-analyzed mixture of SO_2 and CO_2 will be used so that uncertainties in the SO_2 mixing ratio will not be large. We intend to conduct these measurements over a temperature range from 365 K to 550 K, which correspond to the temperatures at altitudes where SO_2 opacity dominates.

These results will then be used in developing a new formalism for describing the opacity of SO_2 under Venus conditions. We expect to integrate these results into our Venus radiative transfer model so as to place better limits on the abundance and distribution of SO_2 in the Venus atmosphere. We will also conduct further work with radio occultation data and emission measurements to better characterize the abundance and distribution of gaseous H_2SO_4 .

IV. PROPOSED PROCEDURE AND LEVEL OF EFFECT

The proposed level of effort in the next grant year (November 1, 1993 through October 31, 1994) involves one professor (P.G. Steffes, Associate Professor of Electrical Engineering) at 25% time, and two graduate students (Graduate Research Assistants David R. DeBoer and Shady Suleiman) at 50% and 9% time,respectively, with supplies and other support as indicated in the attached cost breakdown (see page iv). (Note that 50% is the maximum support level for Ph.D. students with the remaining 50% considered as registered academic thesis research.) In addition to the participation in the program by Professor Steffes and the paid graduate research assistant, contributions to the program from both graduate and undergraduate students working on special projects for academic credit have been substantial. Likewise, in the spirit of the NASA Graduate Student Researchers Program (Underrepresented Minority Focus), we continue to seek out talented underrepresented minority students and involve them in our program.

V. FACILITIES

The specific measurements described in this proposal will be conducted at the Radio Astronomy and Propagation Laboratory and the accompanying Remote Sensing Laboratory, which are located within the School of Electrical Engineering. A description of the equipment being used for these measurements is given in the appended papers.

For support of any required data analysis and computing activities, a wide range of computing services for education, research, and administration is provided by the Georgia Tech Office of Computing Services. Numerous personal computers are also available to support this project.

VI. REFERENCES

DeBoer, D.R. and P.G. Steffes, 1993a. Laboratory measurements of the centimeter-wave characteristics of H_2S under simulated conditions for the outer planets. To be presented at the Fifth International Conference on Laboratory Research for Planetary Atmospheres, Boulder, CO, October 17, 1993. (See Appendix A.)

DeBoer, D.R. and P.G. Steffes, 1993b. Effects of the centimeter wavelength opacity of H_2S on propagation and emission in the atmospheres of the outer planets. To be presented at the 25th Annual Meeting of the Division for Planetary Sciences/American Astronomical Society, Boulder, CO, October 1993. (See Appendix C.)

Fahd, A.K. and P.G. Steffes, 1992. Laboratory measurements of the microwave and millimeter-wave opacity of gaseous sulfur dioxide (SO_2) under simulated conditions for the Venus atmosphere. Icarus 97, 200-210.

Jenkins, J.M. and P.G. Steffes, J. Twicken, D.P. Hinson, and G.L. Tyler, 1993. Radio occultation studies of the Venus atmosphere with the Magellan spacecraft. 2. Results from the October 1991 experiment. To be submitted to Icarus.

Jenkins, J.M. P.G., Steffes, J. Twicken, D.P. Hinson, and G.L. Tyler, 1993b. Atmospheric profiles and sulfuric acid vapor (H_2SO_4) profiles from the october 1991 Magellan orbiter radio occultation experiments at Venus. To be presented at the 25th Annual Meeting of the Division for Planetary Sciences/American Astronomical Society, Boulder, CO, October 1993. (See Appendix E.)

Steffes, P.G., J.M. Jenkins, R.S. Austin, S.W. Asmar, D.T. Lyons, E.H. Seale, and G.L. Tyler, 1993. Radio occultation studies of the Venus atmosphere with the Magellan spacecraft. 1. Experiment description and performance. To be submitted to Icarus. (See Appendix F.)

VII. BIOGRAPHICAL SKETCH

PAUL G. STEFFES
ASSOCIATE PROFESSOR
SCHOOL OF ELECTRICAL ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332-0250

EDUCATION

S.B.	Electrical Engineering	1977
S.M.	Electrical Engineering Massachusetts Institute of Technology	1977
Ph.D.	Electrical Engineering Stanford University	1982

EMPLOYMENT HISTORY

Massachusetts Institute of Technology, Research Laboratory of Electronics, Radio Astronomy and Remote Sensing Group Graduate Research Assistant	1976-1977
Watkins-Johnson Company, Sensor Development, San Jose, California Member of the Technical Staff	1977-1982
Stanford University, Electronics Laboratory, Center for Radar Astronomy, Stanford, California Graduate Research Assistant	1979-1982
Georgia Institute of Technology, School of Electrical Engineering, Atlanta, Georgia Assistant Professor Associate Professor	 1982-1988 1988-Present

EXPERIENCE SUMMARY

At Massachusetts Institute of Technology

Responsible for development, operation, and data analysis for an 8-channel, 118 GHz radiometer system flown aboard the NASA Flying Laboratory (CV-990) as an engineering model for a meteorological sensing satellite. Duties included hardware development of millimeter-wave, microwave, analog, and A to D segments of the system, in addition to airborne operation and reduction of data. The research resulted in a Master's thesis entitled "Atmospheric Absorption at 118 GHz," detailing the first airborne measurement of high altitude atmospheric absorption in the 2.5 millimeter wavelength range, due to atmospheric oxygen.

At Watkins-Johnson Company

Responsibilities included proposals and system design and development, particularly in the area of millimeter-wave systems. Responsibility for millimeter-wave systems development included government sponsored study and development of ELINT (Electronic Intelligence) and radar warning receiving systems to frequencies as high as 110 GHz, as well as internal company sponsored development projects including a 60 GHz communications system and millimeter-wave downconverters.

At Stanford University

Research was concentrated in the area of microwave radio occultation experiments from Voyager and Mariner spacecraft, with specific interest in microwave absorption in planetary atmospheres. Work included computer-based theoretical development of microwave absorption coefficients for planetary atmospheres, to facilitate the use of radio occultation-derived microwave absorption profiles in determining constituent densities. Additional work included the development of a fully instrumented experimental facility for use in measuring the microwave properties of planetary atmospheres under simulated planetary conditions. The research resulted in a Ph.D. dissertation entitled "Abundances of Cloud-Related Gases in the Venus Atmosphere as Inferred from Observed Radio Opacity."

At Georgia Tech

Research Activities: Principal Investigator of the National Science Foundation Grant, "Remote Sensing of Clouds Bearing Acid Rain." This research studied and designed a microwave/millimeter-wave system for remotely sensing the pH of acidic clouds (1982-1983). Principal Investigator of the NASA Planetary Atmospheres Program, "Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres." This research includes study of the interaction between atmospheric constituents and electromagnetic waves, along with application of these studies to spacecraft and radio telescopic measurements of the microwave absorption in atmospheres of Venus and the outer planets (1984-1993). Principal Investigator of the GTE Spacenet Program, "Satellite Interference Locating System (SILS)." The program involved location of uplink signals on the surface of the earth without disrupting regular satellite operations (1986-1990). Principal Investigator of the Emory University/Georgia Tech Biomedical Technology Research Center, "Research in Development of a Non-Invasive Blood Glucose Monitoring Technique." This research involves the use of active infrared systems to determine glucose levels in the human eye and bloodstream (1988-1989), with subsequent support (1990-1991) from Lifescan, Inc. Principal Investigator of the NASA Pioneer Venus Guest Investigator Program, "Pioneer Venus Radio Occultation (ORO) Data Reduction: Profiles of 13 cm Absorptivity." This research infers 13 cm wavelength absorptivity profiles using the Pioneer Venus Orbiter, and then uses such profiles to characterize abundance profiles for gaseous H_2SO_4 in the Venus atmosphere (1988-1990). Principal Investigator/Team Member of NASA High Resolution Microwave Survey (HRMS). This research involves development and operation of the world's most sensitive receiving system used for a 1-10 GHz Sky Survey (1991-1999). Developer of atmospheric radio occultation experiments conducted with the Magellan (Venus) Spacecraft (1991-1992). Director of the Ku Band Satellite Earth Station System. Responsible for development of a Ku-band uplink/downlink system for use in inter-university networks (1985-1992).

Teaching Activities: Resource Professor for "Satellite Communications Systems" (graduate course) and "Electromagnetics III" (undergraduate required course covering waves, waveguides, and antennas). Have also taught "Electromagnetics II" (electrodynamics), "Signals and Systems," and "Survey of Remote Sensing."

HONORS AND AWARDS

1. Member, Eta Kappa Nu.
2. Member, Sigma Xi.
3. Senior Member, IEEE (Member of 6 IEEE Societies).
4. Recipient of the Stewart Award (MIT) for exceptional contribution to student extra-curricular life, 1977.
5. Recipient of the Metro Atlanta Young Engineer of the Year Award, presented by the Society of Professional Engineers, 1985.
6. Recipient of the Sigma Xi Young Faculty Research Award, 1988.
7. Associate Editor, *Journal for Geophysical Research* (JGR-Atmospheres), 1984-1989.
8. Appointed Member of the NASA Management and Operations Working Group for the Planetary Atmospheres Program (1986-1990).
9. Elected to The Electromagnetics Academy, October 1990.
10. Recipient of the Sigma Xi Best Faculty Paper Award, 1991.

OTHER PROFESSIONAL AFFILIATIONS

1. Member, American Association for the Advancement of Science.
2. Member, American Astronomical Society, Division for Planetary Sciences.
3. Member, American Geophysical Union.
4. Member, American Institute of Physics.
5. Member, American Society for Engineering Education.
6. Chairman, Atlanta Chapter, IEEE Antennas and Propagation Society and Microwave Theory and Techniques Society, 1986-1988.
7. Director, IEEE Atlanta Section, 1988-1989.
8. Georgia Tech Chapter, Sigma Xi, Vice President, 1990-1991; President, 1991-1992; Past-President, 1992-1993.
9. Chairman, Publicity Committee, 1993 IEEE International Microwave Symposium.

OTHER PROFESSIONAL ACTIVITIES

1. Proposal Reviewer for the NASA Planetary Astronomy Program, the NASA Planetary Atmospheres Program, the NASA Planetary Instrument Definition and Development Program, the NASA Voyager Data Analysis Programs, and the NASA Exobiology Program.
2. Reviewer/Referee for *Icarus* (International Journal of Solar System Studies), *Journal of Geophysical Research*, *Radioscience*, *IEEE Microwave and Guided Wave Letters*, and for several textbooks in the area of electromagnetics.
3. Consultant to industry in the areas of microwave, millimeter-wave, and RF systems for communications, detection, and monitoring. This includes satellite communications, antenna systems, and propagation.
4. Expert witness in cases involving antenna/communications system performance, and the effects of environmental factors on such systems.

PATENTS

1. E. H. Orr and P. G. Steffes, "Method and System for Detecting Water Depth and Piloting Vessels," Patent # 4,757,481, issued July 12, 1988.

2. R. V. Tarr and P. G. Steffes, "Non-Invasive Blood Glucose Measurement System," Application Serial #07/627,631, filed December 14, 1990.

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Theses

3. P. G. Steffes, "A Microwave (UHF) Television Repeater System," S.B. Thesis, Massachusetts Institute of Technology, 1976.

4. P. G. Steffes, "Atmospheric Absorption at 118 GHz," S.M. Thesis, Massachusetts Institute of Technology, 1977.

5. P. G. Steffes, "Abundances of Cloud-Related Gases in the Venus Atmosphere as Inferred from Observed Radio Opacity," Ph.D. Dissertation, Stanford University, 1982.

Journal Publications

1. P. G. Steffes and R. A. Meck, "Prototype Tests Secure Millimeter Communications," *Microwave Systems News*, vol. 10, pp. 59-68, October 1980.

2. V. R. Eshleman, D. O. Muhleman, P. D. Nicholson, and P. G. Steffes, "Comment on Absorbing Regions in the Atmosphere of Venus as Measured by Radio Occultation," *Icarus*, vol. 44, pp. 793-803, December 1980.

3. P. G. Steffes and V. R. Eshleman, "Sulfur Dioxide and Other Cloud-Related Gases as the Source of the Microwave Opacity of the Middle Atmosphere of Venus," *Icarus*, vol. 46, pp. 127-131, April 1981.

4. P. G. Steffes and V. R. Eshleman, "Laboratory Measurements of the Microwave Opacity of Sulfur Dioxide and Other Cloud-Related Gases Under Simulated Conditions for the Middle Atmosphere of Venus," *Icarus*, vol. 48, pp. 181-187, November 1981.

5. P. G. Steffes and V. R. Eshleman, "Sulfuric Acid Vapor and Other Cloud-Related Gases in the Venus Atmosphere: Abundances Inferred from Observed Radio Opacity," *Icarus*, vol. 51, pp. 322-333, August 1982.

6. P. G. Steffes, "Millimeter-Wavelength Remote Sensing of Stratospheric Sulfur Dioxide," *EOS*, vol. 64, pp. 198-199, May 1983.

7. P. G. Steffes, "Laboratory Measurements of the Microwave Opacity and Vapor Pressure of Sulfuric Acid Under Simulated Conditions for the Middle Atmosphere of Venus," *Icarus*, vol. 64, pp. 576-585, December 1985.

8. P. G. Steffes, "Evaluation of the Microwave Spectrum of Venus in the 1.2 to 22 cm Wavelength Range Based on Laboratory Measurements of Constituent Gas Opacities," *Astrophysical Journal*, vol. 310, pp. 482-489, November 1, 1986.

9. P. G. Steffes and J. M. Jenkins, "Laboratory Measurements of the Microwave Opacity of Gaseous Ammonia (NH_3) Under Simulated Conditions for the Jovian Atmosphere," *Icarus*, vol. 52, pp. 35-47, October 1987.

10. J. M. Jenkins and P. G. Steffes, "Constraints on the Microwave Opacity of Gaseous Methane and Water Vapor in the Jovian Atmosphere," *Icarus*, vol. 76, December 1988.

11. J. Joiner, P. G. Steffes, and J. M. Jenkins, "Laboratory Measurements of the 7.5-9.38 mm Absorption of Gaseous Ammonia (NH_3) Under Simulated Jovian Conditions," *Icarus*, vol. 81, pp. 386-395, 1989.

12. W. W. Smith and P. G. Steffes, "Time Delay Techniques for a Satellite Interference Location System," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 25, pp. 224-231, March 1989.

13. P. G. Steffes, M. J. Klein, and J. M. Jenkins, "Observation of the Microwave Emission of Venus from 1.3 to 3.6 cm," *Icarus*, vol. 84, pp. 83-92, March 1990.

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15. W. W. Smith, Jr. and P. G. Steffes, "A Satellite Interference Location System Using Differential Time and Phase Measurement Techniques," *IEEE Aerospace and Electronic Systems Magazine*, vol. 6, pp. 3-7, March 1991.

16. A. K. Fahd and P. G. Steffes, "Laboratory Measurement of the Millimeter-Wave Properties of Liquid Sulfuric Acid (H_2SO_4)," *Journal of Geophysical Research (Planets)*, vol. 96, pp. 17,471-17,476, September 25, 1991.

17. J. Joiner and P. G. Steffes, "Modeling of the Millimeter-Wave Emission of Jupiter Utilizing Laboratory Measurements of Ammonia (NH_3) Opacity," *Journal of Geophysical Research (Planets)*, vol. 96, pp. 17,463-17,470, September 25, 1991.

18. P. G. Steffes and G. P. Rodrigue, "Comment on Rapid Pulsed Microwave Propagation," *IEEE Microwave and Guided Wave Letters*, vol. 2, pp. 200,201, May 1992.

19. A. K. Fahd and P. G. Steffes, "Laboratory Measurements of the Microwave and Millimeter-Wave Opacity of Gaseous Sulfur Dioxide (SO_2) under Simulated Conditions for the Venus Atmosphere," *Icarus*, vol. 97, pp. 200-210, June 1992.

20. J. Joiner, P. G. Steffes, and K. S. Noll, "Search for Sulfur (H_2S) on Jupiter at Millimeter Wavelengths," *IEEE Transactions on Microwave Theory and Techniques*, vol. 40, pp. 1101-1109, June 1992.

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2. P. G. Steffes and V. R. Eshleman, "Laboratory Measurements of the Microwave Opacity of Cloud Related Gases Under Simulated Conditions for the Venus Atmosphere, *Bulletin of the American Astronomical Society*, vol. 13, pg. 716, 1981.

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5. P. G. Steffes, "Microwave Remote Sensing of Gases and Clouds Involved in the Formation of Acid Precipitation," *Digest of 1983 International Geoscience and Remote Sensing Symposium (IGARSS '83)*, San Francisco, California, vol. 2, no. FA-4, pp. 3.1-3.4, 1983.

6. P. G. Steffes, "A Millimeter-Wave System for the Remote Sensing of Acidic Clouds and Precursor Gases in the Troposphere," *Digest of the Eighth International Conference on Infrared and Millimeter Waves*, Miami Beach, Florida, vol. 1, pp. 264-265, December 16, 1983.

7. P. G. Steffes, P. S. Stellitano, and R. C. Lott, "Measurements of the Microwave Opacity and Vapor Pressure of Gaseous Sulfuric Acid Under Simulated Venus Conditions," *Bulletin of the American Astronomical Society*, vol. 16, pg. 694, 1984.
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10. P. G. Steffes and D. H. Watson, "Constraints on Constituent Abundances in the Venus Atmosphere from the Microwave Emission Spectrum in the 1 to 20 cm Wavelength Range," *Bulletin of the American Astronomical Society*, vol. 17, pg. 720, 1985.
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12. P. G. Steffes, J. M. Jenkins, M. F. Selman, and W. W. Gregory, "Laboratory Measurements of the Microwave Opacity of Gaseous Ammonia (NH_3) Under Simulated Conditions for Jovian Atmospheres," *Bulletin of the American Astronomical Society*, vol. 18, pg. 787, 1986.
Presented at the *18th Annual Meeting of the Division of Planetary Sciences of the American Astronomical Society*, France, November 5, 1986.

13. P. G. Steffes, "Laboratory Measurements of the Millimeter-Wave Absorption from Gaseous Constituents Under Simulated Conditions for the Outer Planets," *Proceedings of the Laboratory Measurements for Planetary Science II Workshop*, Pasadena, California, pp. 6-7 through 6-8, November 9, 1987.

14. J. M. Jenkins and P. G. Steffes, "Limits of the Microwave Absorption of H_2O and CH_4 in the Jovian Atmosphere," *Bulletin of the American Astronomical Society*, vol. 19, pg. 695, 1987.
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15. J. Joiner, J. M. Jenkins, and P. G. Steffes, "Laboratory Measurements of the Opacity of Gaseous Ammonia (NH_3) in the 7.3-8.3 mm (36-41 GHz) Range Under Simulated Conditions for Jovian Atmospheres," *Bulletin of the American Astronomical Society*, vol. 19, pg. 694, 1987.
Presented at the *19th Annual Meeting of the Division of Planetary Sciences of the American Astronomical Society*, Pasadena, California, November 11, 1987.

16. P. G. Steffes, J. M. Jenkins, and M. J. Klein, "Observation of the Microwave Emission Spectrum of Venus from 1.3 to 3.6 cm," *Bulletin of the American Astronomical Society*, vol. 19, pg. 780, 1987.
Presented at the *19th Annual Meeting of the Division of Planetary Sciences of the American Astronomical Society*, Pasadena, California, November 11, 1987.

17. J. M. Jenkins and P. G. Steffes, "Preliminary Results for 13-cm Absorptivity Observed During Pioneer-Venus Radio Occultation Season #10 (1986-87)," *Bulletin of the American Astronomical Society*, vol. 20, pg. 834, 1988.
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18. J. Joiner, J. M. Jenkins, and P. G. Steffes, "Millimeter-Wave Measurements of the Opacity of Gaseous Ammonia (NH_3) Under Simulated Conditions for the Jovian Atmosphere," *Bulletin of the American Astronomical Society*, vol. 20, pg. 867, 1988.
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19. P. G. Steffes, "Laboratory Measurements of Microwave and Millimeter-Wave Properties of Planetary Atmospheric Constituents," *Laboratory Research for Planetary Atmospheres*, NASA Conference Publication CP-3077, pp. 5-26, 1990.
Presented at the *First International Conference for Laboratory Research for Planetary Atmospheres*, Bowie, Maryland, October 1989. (invited)

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21. P. G. Steffes, "Evidence for Temporal Variations in SO_2 Abundance in the Sub-Cloud Region of the Venus Atmosphere," *Bulletin of the American Astronomical Society*, vol. 21, pg. 925, 1989.
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22. A. K. Fahd and P. G. Steffes, "Laboratory Measurements of the Dissociation Factor of Gaseous Sulfuric Acid (H_2SO_4)," *Bulletin of the American Astronomical Society*, vol. 21, pg. 927, 1989.
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23. J. Joiner and P. G. Steffes, "Models of the Millimeter-Wave Emission of the Jovian Atmosphere Utilizing Laboratory Measurements of Gaseous Ammonia (NH_3)," *Bulletin of the American Astronomical Society*, vol. 21, pg. 945, 1989.
Presented at the *21st Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society*, Providence, Rhode Island, November 1, 1989.

24. W. W. Smith and P. G. Steffes, "A Satellite Interference Location System using Differential Time and Phase Measurement Techniques," *Proceedings of the IEEE International Carnahan Conference on Security Technology: Crime Countermeasures*, publ. no. 90CH2892-8, pps. 38-41, 1990.
Presented at the *IEEE International Carnahan Conference on Security Technology: Crime Countermeasures*, Lexington, Kentucky, October 11, 1990.

25. A. K. Fahd and P. G. Steffes, "Laboratory Measurements of the 1.3 and 13.3 cm Opacity of Gaseous SO_2 under Simulated Conditions of the Middle Atmosphere of Venus," *Bulletin of the American Astronomical Society*, vol. 22, pg. 1032, 1990.
Presented at the *22nd Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society*, Charlottesville, Virginia, October 22, 1990.

26. A. K. Fahd and P. G. Steffes, "Laboratory Measurement of the Millimeter-Wave Properties of Liquid Sulfuric Acid (H_2SO_4) Between 90 and 100 GHz," *Bulletin of the American Astronomical Society*, vol. 22, pg. 1035, 1990.
Presented at the *22nd Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society*, Charlottesville, Virginia, October 22, 1990.

27. J. Joiner and P. G. Steffes, "Study of Millimeter-Wave Absorbing Constituents in the Jovian Atmospheres," *Bulletin of the American Astronomical Society*, vol. 22, pg. 1032, 1990.
Presented at the *22nd Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society*, Charlottesville, Virginia, October 22, 1990.

28. J. M. Jenkins and P. G. Steffes, "Sulfuric Acid Vapor Profiles for the Atmosphere of Venus Below the Main Cloud Deck," *Bulletin of the American Astronomical Society*, vol. 22, pg. 1055, 1990.
Presented at the *22nd Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society*, Charlottesville, Virginia, October 23, 1990.

29. P. G. Steffes and J. M. Jenkins, "Atmospheric Radio Occultation Measurements with Magellan at Venus," *JPL Publication*, JPL-D-8581, pp. B1-B8, 1991.
Presented at the *Magellan Atmospheric Science and Science Contingency Workshop*, Pasadena, California, May 7, 1991.

30. P. G. Steffes, "The Potential for Millimeter-Wave SETI," *Publications of the Astronomical Society of the Pacific*, in press.
Presented at the *USA-USSR Joint Conference on the Search for Extraterrestrial Intelligent Life*, Santa Cruz, California, August 9, 1991.

31. A. K. Fahd and P. G. Steffes, "Laboratory Measurements of the Millimeter-Wave Opacity of Gaseous Sulfuric Acid (H_2SO_4) under Venus-Like Conditions," to be published in the *Proceedings of the Third International Conference on Laboratory Research for Planetary Atmospheres*.
Presented at the *Third International Conference on Laboratory Research for Planetary Atmospheres*, Palo Alto, California, Paper SP-20, November 3, 1991.

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Presented at the *23rd Meeting of the Division for Planetary Sciences of the American Astronomical Society*, Palo Alto, California, November 6, 1991.

34. J. M. Jenkins and P. G. Steffes, "Comparison of Kalman and Wiener Filtering Techniques for Processing Pioneer Venus Radio Occultation Data," *Bulletin of the American Astronomical Society*, vol. 23, p. 1195, November 1991.
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35. P. G. Steffes, J. M. Jenkins, R. S. Austin, G. L. Tyler, and E. H. Seale, "Radio Occultation Studies of the Venus Atmosphere with the Magellan Spacecraft," *Bulletin of the American Astronomical Society*, vol. 23, p. 1196, November 1991.
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FEBRUARY 1993

APPENDIX A: To be presented at the Fifth International Conference on Laboratory Research for Planetary Atmospheres, Boulder, CO, October 17, 1993.

Laboratory Measurements of the Centimeter-Wave Characteristics of H_2S Under Simulated Conditions for the Outer Planets[1]

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The large abundance of ammonia (NH_3) in the atmospheres of Jupiter and Saturn has to date precluded detection of any absorption at millimeter or centimeter wavelengths due to hydrogen sulfide (H_2S), a molecule hypothesized to exist in the deep atmospheric layers of the outer planets (see e.g., Joiner et al., 1992, IEEE Trans. MTT **40**:1101). Uranus and Neptune, however, are depleted in ammonia and thus H_2S opacity may significantly affect their brightness temperatures at those wavelengths. (de Pater and Mitchell, 1993, JGR-Planets **98**:5471). Though the rotational line centers of H_2S are in the millimeter wavelength region, absorption is present at centimeter wavelengths due to pressure broadening of the lines. Accordingly, the properties of H_2S in an H_2/He environment at 2, 4 and 6 atmospheres and at 290 K, 213 K and 193 K have been measured at 2.25 GHz (13.3 cm), 8.5 GHz (3.5 cm) and 21.7 GHz (1.4 cm). The mixture at 290 K and 213 K was approximately 12% H_2S, 79% H_2 and 9% He, while at 193 K it was 4% H_2S, 93% H_2 and 3% He (to avoid condensation of H_2S). One interesting feature measured was the very high microwave refractivity of H_2S (8.85×10^{-17} N-units/molecule/cm^3) which is more than 8 times greater than that of N_2. This hyper-refractivity made the effects of dielectric loading quite prominent during our absorptivity measurements (see e.g., Joiner, Steffes and Jenkins, 1989, Icarus **81**:386). These measurements show values that are significantly greater than values predicted by Van Vleck-Weisskopf models, even using the new value for the H_2S line broadening parameter developed by Joiner et al. (1992). Alternate line shape formulations and new measurements are being developed to better characterize these new results.

[1]This work was supported by the NASA Planetary Atmospheres Program under grant NAGW-533.

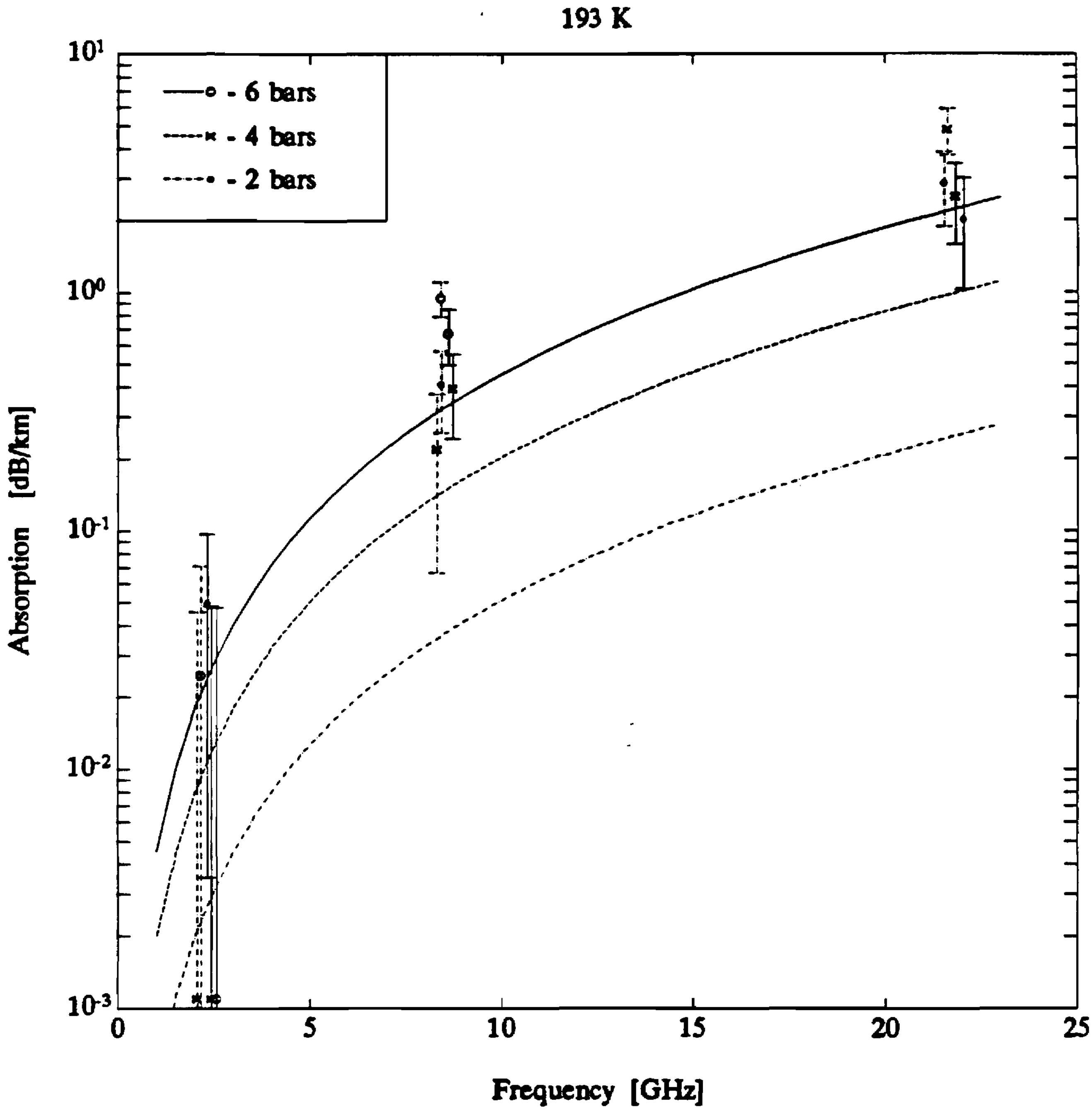

Figure 1: 193 K H_2S attenuation measured on two different dates: June 2, 1993 (solid error bars) and May 5, 1993 (dot-dashed error bars). The curves are Van Vleck-Weisskopf line shapes as developed by Joiner et. al. (1992, IEEE Trans.-MTT, 40:1101) for 6 bars, 4 bars and 2 bars (solid line, dashed line and dot-dashed line respectively) and a mixture of 93% H_2, 3%He and 4% H_2S at a temperature of 193 K. See tables 1 and 2. The frequencies in a given band have been spread slightly for purposes of plotting. Data points lying near the bottom line (10^{-3}) indicate upper boundaries for that measurement.

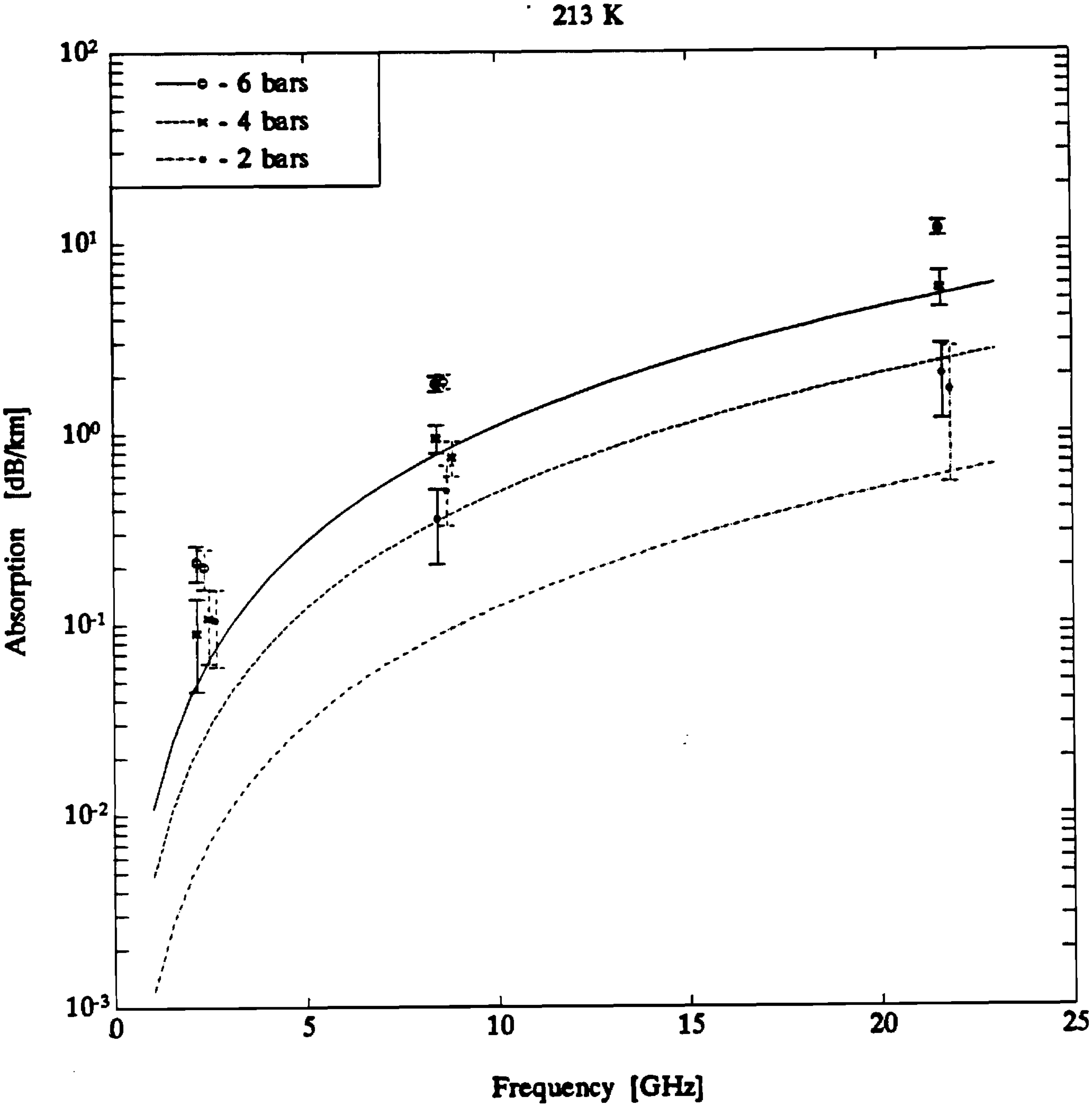

Figure 2: 213 K H_2S attenuation measured on two different dates: June 9, 1993 (solid error bars) and April 21, 1993 (dot-dashed error bars). The curves are Van Vleck-Weisskopf line shapes as developed by Joiner et. al. (1992, IEEE Trans.-MTT, 40:1101) for 6 bars, 4 bars and 2 bars (solid line, dashed line and dot-dashed line respectively) and a mixture of 79% H_2, 9%He and 12% H_2S at a temperature of 213 K. See tables 3 and 4. The frequencies in a given band have been spread slightly for purposes of plotting.

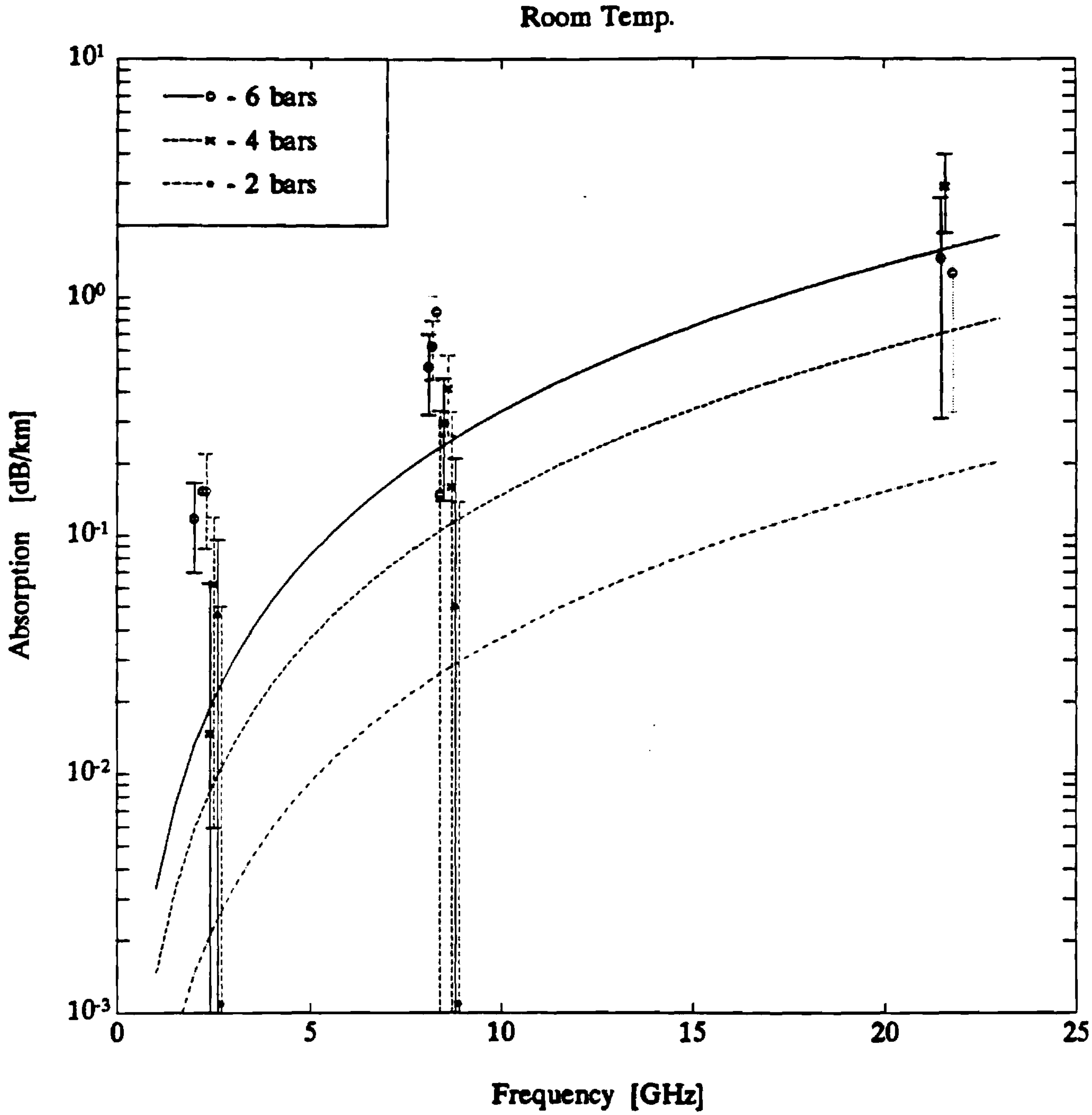

Figure 3: Room temperature H_2S attenuation measured on four different dates: June 21, 1993 (solid error bars); February 26, 1992 (dotted error bars); January 29, 1993 (dashed error bars); and February 5, 1993 (dot-dashed error bars). The curves are Van Vleck-Weisskopf line shapes as developed by Joiner et. al. (1992, IEEE Trans.-MTT, 40:1101) for 6 bars, 4 bars and 2 bars (solid line, dashed line and dot-dashed line respectively) and a mixture of 79% H_2, 9%He and 12% H_2S at a temperature of 293 K. See tables 5-8. The frequencies in a given band have been spread slightly for purposes of plotting. Data points lying near the bottom line (10^{-3}) indicate upper boundaries for that measurement.

	S (2.25 GHz)	X (8.5 GHz)	K (21.7 GHz)
6 bar	≤ 0.036	0.675 ± 0.177	—
4 bar	≤ 0.046	0.398 ± 0.154	2.518 ± 0.934
2 bar	0.050 ± 0.047	—	2.019 ± 0.991

Table 1: H_2S Absorption at 193 K in dB/km: June 2, 1993. Pressure = 6.21, 4.10, 2.03 bars. Mixture: 93.14% H_2, 2.94% He, 3.92% H_2S. N_2 was used to account for dielectric loading. See appendix B for calculation of the attenuation and error.

	S (2.25 GHz)	X (8.5 GHz)	K (21.7 GHz)
6 bar	0.025 ± 0.046	0.951 ± 0.161	—
4 bar	≤ 0.021	0.221 ± 0.154	4.812 ± 1.059
2 bar	—	0.413 ± 0.155	2.867 ± 0.988

Table 2: H_2S Absorption at 193 K in dB/km: May 5, 1993. Pressure = 6.17, 4.17, 2.03 bars. Mixture: 93.03% H_2, 3.02% He, 3.95% H_2S. N_2 was used to account for dielectric loading as above however the vacuum values used were not re-measured immediately prior to the nitrogen measurements and hence spectrum analyser drift was not properly accounted for.See appendix B for calculation of the attenuation and error.

	S (2.25 GHz)	X (8.5 GHz)	K (21.7 GHz)
6 bar	0.215 ± 0.045	1.828 ± 0.171	11.705 ± 1.039
4 bar	0.090 ± 0.046	0.947 ± 0.160	5.731 ± 1.233
2 bar	—	0.360 ± 0.153	2.026 ± 0.857

Table 3: H_2S Absorption at 213 K in dB/km: June 9, 1993. Pressure = 6.21, 4.10, 2.03 bars. Mixture: 79.03% H_2, 8.98% He, 11.99% H_2S. N_2 was used to account for dielectric loading, however enough nitrogen could not be added at 6 bars to match the H_2S refractivity due to safety considerations.See appendix B for calculation of the attenuation and error.

	S (2.25 GHz)	X (8.5 GHz)	K (21.7 GHz)
6 bar	0.201 ± 0.047	1.876 ± 0.162	—
4 bar	0.108 ± 0.046	0.752 ± 0.157	—
2 bar	0.106 ± 0.046	0.504 ± 0.176	1.669 ± 1.127

Table 4: H_2S Absorption at 213 K in dB/km: April 21, 1993. Pressure = 6.17, 4.17, 2.03 bars. Mixture: 79.09% H_2, 9.07% He, 11.84% H_2S. A hydrogen/helium mixture was used to try and account for dielectric loading where we used a 74%/26% mixture at 6.17, 4.17 and 2.03 bars. However, due to the fact that H_2S provided the bulk of the dielectric loading this method gave poor results.See appendix B for calculation of the attenuation and error.

	S (2.25 GHz)	X (8.5 GHz)	K (21.7 GHz)
6 bar	0.118 ± 0.048	0.513 ± 0.191	1.458 ± 1.149
4 bar	0.015 ± 0.048	0.299 ± 0.160	2.927 ± 1.066
2 bar	0.047 ± 0.049	0.051 ± 0.160	—

Table 5: H_2S Absorption at 293 K in dB/km: June 21, 1993. Pressure = 6.17, 4.10, 2.03 bars. Mixture: 79.03% H_2, 8.98% He, 11.99% H_2S. N_2 was used to account for dielectric loading, however, again we could not match the refractivity at 6 bars due to safety considerations. See appendix B for calculation of the attenuation and error.

	S (2.25 GHz)	X (8.5 GHz)	K (21.7 GHz)
6 bar	0.154 ± 0.048	0.871 ± 0.146	1.263 ± 0.936

Table 6: H_2S Absorption at 297 K in dB/km: February 26, 1992. Pressure = 6.17 bars. Mixture: 79% H_2, 9% He, 12% H_2S. A scheme identical to 4/21/93 using H_2/He was used to account for loading effects. See appendix B for calculation of the attenuation and error.

	S (2.25 GHz)	X (8.5 GHz)
6 bar	0.154 ± 0.066	0.149 ± 0.185
4 bar	0.062 ± 0.056	0.161 ± 0.170
2 bar	≤ 0.048	≤ 0.139

Table 7: H_2S Absorption at 291 K in dB/km: January 29, 1993. Pressure = 6.17, 4.10, 2.03 bars. Mixture: 79.00% H_2, 8.99% He, 12.01% H_2S. The H_2/He scheme was used to account for loading effects. See appendix B for calculation of the attenuation and error.

	X (8.5 GHz)
6 bar	0.626 ± 0.174
4 bar	0.418 ± 0.156

Table 8: H_2S Absorption at 293 K in dB/km: February 5, 1993. Pressure = 6.10, 4.10 bars. Mixture: 79.00% H_2, 8.99% He, 12.01% H_2S. An attempt to use just H_2 to account for dielectric loading was tried, however the refractivity at no pressure was matched.See appendix B for calculation of the attenuation and error.

APPENDIX B

H_2S Data Reduction

David DeBoer

July 7, 1993

1 Calculating Absorption of a Lossy Gas Using Q

Calculating microwave opacity from a weakly absorbing gas mixture using a resonator requires measuring the quality factor of that resonator which necessitates accurately determining the center frequency (f_o) and the half power bandwidth (Δf) of a noisy resonant line. The center frequency can be determined very accurately and varies very little over many measurements (a few kHz at GHz frequencies or a few hundredths of a percent). The greater source of error in estimating the Q of a resonator comes from the bandwidth measurements. The half power bandwidth is determined essentially by eye-fitting a curve over a noisy resonant line and measuring with a spectrum analyzer.

Assuming uncorrelated measurement error (an unbiased observer) the best estimation of the bandwidth is obviously the mean of many measurements. Therefore,

$$\Delta f \approx \frac{1}{N}\sum_{i=1}^{N}\Delta f_i \tag{1}$$

where Δf_i are the individual bandwidth measurements. To determine the accuracy of the measurements we calculate the sample variance,

$$S_N^2 = \frac{1}{N-1}\sum_{i=1}^{N}(\Delta f_i - \Delta f)^2 \tag{2}$$

and finally the variance of our estimation from the "true" bandwidth due to electrical noise,

$$\sigma_N^2 = \frac{t_\sigma^2}{N}S_N^2 \tag{3}$$

where t_σ is the "student-t" for the 1σ confidence level given a Gaussian distribution. Recall that the student-t is a distribution to characterize the confidence level of a finite sample set where the degrees of freedom are the number of samples. For ten measurements, $t_\sigma = 1.1$ [5, pp. 255, 260].

One can also calculate some figures of merit to determine the stationarity of the data [5, pp. 255-6]. Divide the ten measurements into two groups of five and calculate the sample variance (s_1^2, s_2^2) and mean (m_1, m_2) of each group where $s_1 > s_2$ and $m_1 > m_2$. We can define a figure of merit for stationarity of the variance as $F_o = 0.156 s_1^2/s_2^2$. If $F_o < 1$ then the variance is likely to be stationary. For the mean, we define $t_o = 0.974(m_1 - m_2)/\sqrt{s_1^2 + s_2^2}$ as the figure of merit and if $t_o < 1$ then the mean is likely to be stationary. If either one of these conditions does not hold the measurement is not stationary and should be considered suspect.

There are also instrument errors which must be taken into consideration as well. These stem from the limited accuracy of the spectrum analyzer and are calculated as follows [2]:

$$\sigma_o \approx 10^{-5} f_o + 0.15\mathrm{RBW} + 0.05\mathrm{SPAN} + L_o + 250 \quad \mathrm{Hz} \tag{4}$$

$$\sigma_\Delta \approx 10^{-5}\text{BW} + 200N + 4L_{BW} \quad \text{Hz} \tag{5}$$

where σ_o is the standard deviation of the center frequency measurement due to the spectrum analyzer accuracy, σ_Δ the standard deviation of the bandwidth measurement, RBW is the resolution bandwidth, L the least significant digit, BW the bandwidth and N the harmonic number (see tables 1 and 2).

Freq. band	S	X	K
RBW [Hz]	300	1000	30000
SPAN [kHz]	50	100	2000
N	1	2	4
L_o	10	100	1000
L_{BW}	10	100	1000

Table 1: Spectrum analyzer parameters

	σ_o [kHz]	σ_Δ [Hz]
S	25	240
X	90	800
K	320	4815

Table 2: Instrument uncertainty for the frequency bands.

It is then possible to estimate the measured bandwidth and characterize its uncertainty. What we measure from a conventional spectrum analyzer, however, is not the true spectrum of the resonator but rather the convolution of the resonator spectrum and the sweep filter spectrum. If $Y(f)$ is the output, $X(f)$ the input and $H(f)$ the filter, then

$$Y(f) = H(f) * X(f). \tag{6}$$

In the time domain, we have $y(t) = h(t)x(t)$ where $y(t)$ is the inverse Fourier transform of Y(f) and so on. Therefore, the signal spectrum is,

$$X(f) = \mathcal{F}[y(t)/h(t)] \tag{7}$$

where $\mathcal{F}[\cdot]$ denotes a Fourier Transform. If we assume a Gaussian filter and a Gaussian input then the actual signal bandwidth is simply

$$\Delta f_Q = \sqrt{\Delta f^2 - \text{RBW}^2} \tag{8}$$

where Δf_Q is the "true" half power bandwidth and Δf is the measured mean bandwidth. The Q of the resonator is then simply

$$Q = \frac{f_o}{\Delta f_Q}. \tag{9}$$

We will discuss the error in the next section.

To calculate the absorption recall that

$$\frac{\alpha}{\beta} = \sqrt{\frac{\sqrt{1 + (\epsilon''/\epsilon')^2} - 1}{\sqrt{1 + (\epsilon''/\epsilon')^2} + 1}} \tag{10}$$

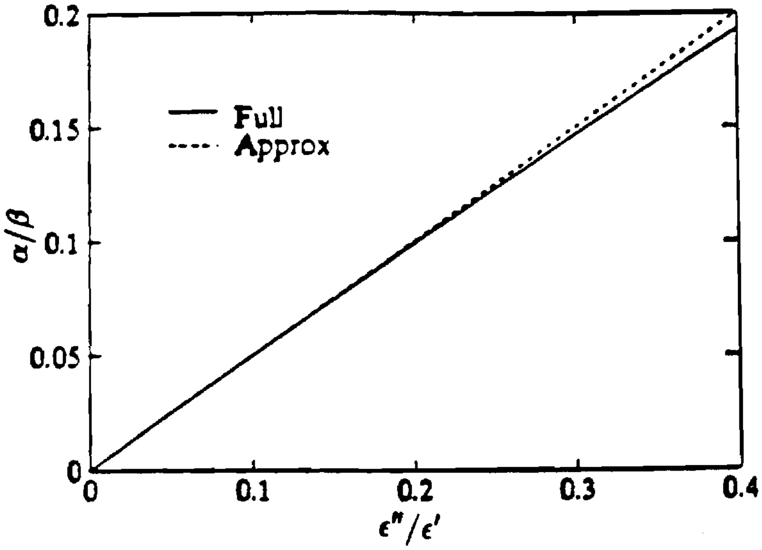

Figure 1: α/β vs. ϵ''/ϵ' for full expression (eq. 10) and approximation (eq. 11).

where $\beta = 2\pi/\lambda$ (with the gas present), α is the absorption and $\epsilon = \epsilon' - j\epsilon''$ the complex permittivity. Since $\epsilon'' \ll \epsilon'$ for gases in the microwave region this reduces to

$$\frac{\alpha}{\beta} \approx \frac{\epsilon''}{2\epsilon'}. \tag{11}$$

Note that this is field attenuation—to get power attenuation one must multiply this by 2.

The Q of a dielectric, Q_d, is given by

$$Q_d = \frac{1}{tan\delta} = \frac{\omega\epsilon'}{\omega\epsilon'' + \sigma} \approx \frac{\epsilon'}{\epsilon''} \tag{12}$$

where the approximation holds for a gas at microwave frequencies. Therefore, we see that

$$\alpha \approx \frac{\beta}{2Q_d} = \frac{\pi}{\lambda}\frac{1}{Q_d}. \tag{13}$$

To determine Q_d we must examine the Q of a lossy, coupled resonator.

The measured quality factor of an evacuated resonator can be given by [1, p. 404]

$$\frac{1}{Q_{Tv}} = \frac{1}{Q_{Cv}} + \frac{1}{Q_{ev(1)}} + \frac{1}{Q_{ev(2)}} \tag{14}$$

and in the presence of a lossy gas

$$\frac{1}{Q_{Tg}} = \frac{1}{Q_{Cg}} + \frac{1}{Q_d} + \frac{1}{Q_{eg(1)}} + \frac{1}{Q_{eg(2)}} \tag{15}$$

where

$$\begin{aligned} Q_{Tv,g} &= \text{the total (measured) Q without and with the gas} \\ Q_{Cv,g} &= \text{cavity Q without and with the gas} \\ Q_{ev,g(1,2)} &= \text{external Q on both sides without and with the gas} \\ Q_d &= \text{Q of the gas.} \end{aligned}$$

Since a symmetrical cavity is used, assume that $Q_{eg.v(1)} = Q_{eg.v(2)} \doteq Q_{eg.v}$. Additionally [1, p. 404]

$$\frac{\sqrt{t_{g.v}}}{2Q_{Tg.v}} = \frac{1}{Q_{eg.v}} \tag{16}$$

where t_g and t_v are the transmissivities of the resonator at resonance with and without the gas respectively (assuming a lossless gas). Substituting into equations 14 and 15, subtracting and solving for $1/Q_d$ yields

$$\frac{1}{Q_d} = \frac{1-\sqrt{t_g}}{Q_{Tg}} - \frac{1-\sqrt{t_v}}{Q_{Tv}} + \frac{1}{Q_{Cv}} - \frac{1}{Q_{Cg}}. \tag{17}$$

Note that $Q_{Cv,g}$ takes conductivity losses and diffraction losses into account. The Q for finite conductivity, Q_σ, of a circular cavity varies as $1/\sqrt{f}$ [3, p. 352] we see therefore that

$$\frac{Q_{\sigma,v}}{Q_{\sigma,g}} = \sqrt{\frac{f_g}{f_v}} \approx 1. \tag{18}$$

For diffraction, likewise, the ratios of the Q's will be on the order of the ratios of the wavelengths and also equal to about 1, therefore $Q_{Cv} \approx Q_{Cg}$. Substituting these approximations into 17 yields

$$\frac{1}{Q_d} = \frac{1-\sqrt{t_g}}{Q_{Tg}} - \frac{1-\sqrt{t_v}}{Q_{Tv}}. \tag{19}$$

Recall that t_g assumes a lossless gas. Actually, the measured transmissivity, $t_{g,meas}$, equals $t_g e^{-\alpha d_{eff}}$ or

$$t_g = t_{g,meas} e^{\alpha d_{eff}} \tag{20}$$

where $d_{eff} = Q\lambda/2\pi$ is the effective path length of the resonator. We can then solve iteratively for the actual α.

We therefore see that

$$\alpha = \frac{\pi}{\lambda}\left(\frac{1-\sqrt{t_g}}{Q_{Tg}} - \frac{1-\sqrt{t_v}}{Q_{Tv}}\right) \quad \text{Nepers/m} \tag{21}$$

where λ is in meters. In dB, we can express α as

$$\alpha_{dB} = 8.686\frac{\pi}{\lambda}\left(\frac{1-\sqrt{t_g}}{Q_{Tg}} - \frac{1-\sqrt{t_v}}{Q_{Tv}}\right) \quad \text{dB/m}. \tag{22}$$

The above analysis neglects the effects of dielectric loading [4]. Using an amount of lossless gas with the same refractivity value as the lossy gas in lieu of merely an evacuated resonator will remove the effects of the dielectric loading, provided you are far enough from the line center of the absorption line so that anomalous dispersion is not present.

2 Calculating the Error

Define a quantity

$$\xi = g(f_{og}, \Delta f_g, f_{ov}, \Delta f_v) = \frac{\gamma_g \Delta f_g}{f_{og}} - \frac{\gamma_v \Delta f_v}{f_{ov}} \tag{23}$$

where Δf_g and Δf_v are the loaded and unloaded half power bandwidths and f_{og} and f_{ov} are the loaded and unloaded center frequencies. We define this quantity since we wish to ignore the $1/\lambda$ dependence in front of α in the interest of symmetry. Then to first order

$$\begin{aligned}
\delta\xi &= \frac{\partial g}{\partial f_{og}}\delta f_{og} + \frac{\partial g}{\partial \Delta f_g}\delta\Delta f_g + \frac{\partial g}{\partial f_{ov}}\delta f_{ov} + \frac{\partial g}{\partial \Delta f_v}\delta\Delta f_v \\
&= \frac{\gamma_v}{f_{ov}}\left[\frac{\Delta f_v \delta f_{ov}}{f_{ov}} - \delta\Delta f_v\right] - \frac{\gamma_g}{f_{og}}\left[\frac{\Delta f_g \delta f_{og}}{f_{og}} - \delta\Delta f_g\right] \\
&\equiv \Gamma_v - \Gamma_g.
\end{aligned} \tag{24}$$

Note that this ignores variation in $\gamma = 1 - \sqrt{t}$.

Assume that $< \delta\xi >= 0$ that is, we are dealing with sero-mean processes; therefore

$$\sigma_\xi^2 =< \delta\xi^2 >=< \Gamma_v^2 > + < \Gamma_g^2 > -2 < \Gamma_g \Gamma_v > \tag{25}$$

where

$$< \Gamma_i^2 > = \frac{\gamma_i^2}{f_{oi}^2}\left[\frac{< \delta f_{oi}^2 >}{Q_i^2} + < \delta\Delta f_i^2 > - \frac{2 < \delta f_{oi}\delta\Delta f_i >}{Q_i}\right] \qquad i = v, g \tag{26}$$

$$< \Gamma_v \Gamma_g > = \frac{\gamma_v \gamma_g}{f_{og} f_{ov}}\left[\frac{< \delta f_{og}\delta f_{ov} >}{Q_g Q_v} + < \delta\Delta f_g \delta\Delta f_v > - \frac{< \delta f_{og}\delta\Delta f_v >}{Q_g} - \frac{< \delta f_{ov}\delta\Delta f_g >}{Q_v}\right] \tag{27}$$

$$Q_i = \frac{f_{oi}}{\Delta f_i}. \tag{28}$$

The bandwidth variation consists of instrument accuracy and noise; i.e. $\delta\Delta f_i = \delta\Delta f_{SA} + \delta\Delta f_{Ni}$. Throughout, we will assume that electrical noise and the spectrum analyser accuracy are uncorrelated. Since we have assumed sero-mean processes and uncorrelated accuracy/noise then

$$< \delta f_{oi}^2 > = \sigma_o^2 \tag{29}$$

$$< \delta\Delta f_i^2 > = \sigma_\Delta^2 + \sigma_{Ni}^2. \tag{30}$$

The uncertainty of the measured gas absorption, α, is then

$$\pm \frac{8.686\pi}{\lambda}\sigma_\xi \qquad \text{dB/m} \tag{31}$$

where we have neglected the uncertainty in the measurement of λ. There are three cases that we will consider: the uncorrelated case, the "worst" correlation case and the "best" correlation case.

2..1 Uncorrelated Case

In the uncorrelated case, where naturally all variations are uncorrelated with one another, we find that

$$< \Gamma_i^2 >= \frac{\gamma_i^2}{f_{oi}^2}\left[\frac{\sigma_o^2}{Q_i^2} + \sigma_\Delta^2 + \sigma_{Ni}^2\right] \tag{32}$$

$$< \Gamma_g \Gamma_v >= 0. \tag{33}$$

2..2 Worst Case

In the worst case scenario (the greatest error), $\delta f_v \delta\Delta f_g$ and $\delta f_g \delta\Delta f_v$ terms are completely correlated while the other terms are completely anti-correlated and, of course, the electrical noise terms are uncorrelated with the instrument accuracy terms. This yields

$$< \Gamma_i^2 > = \frac{\gamma_i^2}{f_{oi}^2}\left[\frac{\sigma_o^2}{Q_i^2} + \sigma_\Delta^2 + \sigma_{Ni}^2 + \frac{2\sigma_o\sigma_\Delta}{Q_i}\right] \tag{34}$$

$$< \Gamma_v \Gamma_g > = -\frac{\gamma_v \gamma_g}{f_{og} f_{ov}}\left[\frac{\sigma_o^2}{Q_g Q_v} + \sigma_\Delta^2 + \frac{\sigma_o\sigma_\Delta}{Q_g} + \frac{\sigma_o\sigma_\Delta}{Q_v}\right]. \tag{35}$$

This is the case typically used for the error, since a few small error terms have been neglected in this derivation.

2..3 Best Case

The best case scenario is the reverse of the worst case; that is $\delta f_v \delta\Delta f_g$ and $\delta f_g \delta\Delta f_v$ terms are completely anti-correlated while the other terms are completely correlated. This yields

$$< \Gamma_i^2 > \;=\; \frac{\gamma_i^2}{f_{oi}^2}\left[\frac{\sigma_o^2}{Q_i^2} + \sigma_\Delta^2 + \sigma_{Ni}^2 - \frac{2\sigma_o\sigma_\Delta}{Q_i}\right] \tag{36}$$

$$< \Gamma_v\Gamma_g > \;=\; \frac{\gamma_v\gamma_g}{f_{og}f_{ov}}\left[\frac{\sigma_o^2}{Q_gQ_v} + \sigma_\Delta^2 + \frac{\sigma_o\sigma_\Delta}{Q_g} + \frac{\sigma_o\sigma_\Delta}{Q_v}\right]. \tag{37}$$

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APPENDIX C:

Effects of the Centimeter Wavelength Opacity of H_2S on Propagation and Emission in the Atmospheres of the Outer Planets[1]

D. R. DeBoer, P. G. Steffes (Georgia Institute of Technology)

Recently, measurements of the microwave properties of H_2S have been taken under simulated conditions for the outer planets (DeBoer and Steffes, 1993, Laboratory Research for Planetary Atmospheres Conference). This is especially significant for Uranus and Neptune since they appear to be depleted in NH_3 and thus H_2S may significantly affect the emission from those planets (de Pater et al., 1991, Icarus 91:220). These measurements show values that are significantly greater than values predicted by Van Vleck-Weisskopf models, even using the new value for the H_2S line broadening parameter developed by Joiner et al. (1992, IEEE Trans. MTT, 40:1101). In addition to the strong opacity (relative to the Van Vleck-Weisskopf line shape function) the hyper-refractivity of the H_2S molecule (8.85×10^{17} N-units/molecule/cm^3—8 times greater than that of nitrogen) has consequences for the interpretation of observational data. Radiative transfer models which utilize these results are being developed for Uranus and Neptune. The most recent radiative transfer models will be presented and the conclusions to date will be summarized.

[1]This work was supported by the NASA Planetary Atmospheres Program under grant NAGW-533.

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APPENDIX D:

Using the GEISA and Poynter-Pickett Catalogs

David DeBoer

July 7, 1993

1 Using the GEISA Catalog

The GEISA catalog gives the following information on molecular lines in the following units:

ν_o [cm^{-1}]	S(T$_o$) [cm^{-1}/molecule/cm^2]	E$_l$ [cm^{-1}]	$\Delta\nu_o$ [cm^{-1}/atm]

where ν_o is the line center frequency, S(T$_o$) is the line intensity at a reference temperature (296 K), E$_l$ is the energy of the lower state and $\Delta\nu_o$ is the line broadening parameter at the reference temperature. To get the intensity for another temperature, calculate

$$S(T) = S(T_o)\left(\frac{T_o}{T}\right)^{\eta+1} e^{-(hc/k)E_l(1/T-1/T_o)} \qquad \text{cm/molecule.} \tag{1}$$

Recall that $E(\text{erg}) = hcE(\text{cm}^{-1})$ where c is the speed of light in cm/sec and h is Planck's constant in erg-s, which accounts for the hc in the exponent. For non-linear and symmetric-top molecules $\eta \approx 3/2$, while for linear molecules $\eta \approx 1$. Note the extra T^{-1} dependence—this stems from approximating the "true" exponential term to get the form above, that is:

$$\frac{e^{-hcE_h/kT} - e^{-hcE_l/kT}}{e^{-hcE_h/kT_o} - e^{-hcE_l/kT_o}} = \frac{e^{-hcE_l/kT}}{e^{-hcE_l/kT_o}}\left[\frac{e^{-(hcE_h-hcE_l)/kT}-1}{e^{-(hcE_h-hcE_l)/kT_o}-1}\right] \approx \left(\frac{T_o}{T}\right) e^{-hcE_l/k(1/T-1/T_o)}. \tag{2}$$

At the line center

$$\alpha_{max} = \frac{nS(T)}{\pi\Delta\nu} \qquad \text{cm}^{-1} \tag{3}$$

where

$$n = \frac{N_oP}{RT} \qquad \text{molecule/cm}^3 \tag{4}$$

is the number density. Using $N_o = 6.02297 \times 10^{23}$ [mole^{-1}] as Avogadro's number, $R = 8.31432 \times 10^7$ [erg/mole-K] as the molar gas constant, and T in K requires P to be given in dyne/cm^2. To convert, note that P(dynes/cm^2) = 1.01325 x 10^{6}P(atm). Putting this all together for α_{max} yields,

$$\alpha_{max} = 1.01325 \times 10^6 \frac{N_oP(\text{atm})}{\pi RT\Delta\nu(\text{cm}^{-1})}\left(\frac{T_o}{T}\right)^{\eta+1} S(T_o)e^{-(hc/k)E_l(1/T-1/T_o)} \qquad \text{cm}^{-1} \tag{5}$$

where N_o, and R are given above. Substituting these values in and consolidating the temperature dependence yields a slightly condensed form:

$$\alpha_{max} = 7.34 \times 10^{21} \frac{P(\text{atm})}{T_o\pi\Delta\nu(\text{cm}^{-1})}\left(\frac{T_o}{T}\right)^{\eta+2} S(T_o)e^{-(hc/k)E_l(1/T-1/T_o)} \qquad \text{cm}^{-1}. \tag{6}$$

The linewidth can be calculated from the line broadening parameter as follows,

$$\Delta\nu = \Delta\nu_o P \left(\frac{T_o}{T}\right)^{\epsilon} \qquad \mathrm{cm}^{-1} \tag{7}$$

where P is in atmospheres. If $\Delta\nu_o$ is in units of GHz/atm then

$$\Delta\nu(\mathrm{cm}^{-1}) = \frac{1}{29.9792458}\Delta\nu_o(\mathrm{GHz/atm})P(\mathrm{atm})\left(\frac{T_o}{T}\right)^{\epsilon} \qquad \mathrm{cm}^{-1} \tag{8}$$

since $\nu(\mathrm{GHz}) = (c/10^9)\nu(\mathrm{cm}^{-1})$ where c is the speed of light in cm/sec. If there is more than one broadening agent then the partial pressure-broadening parameter-temperature dependence products must be summed in lieu of just using eq. 7

To examine the temperature dependence of the linewidth note that

$$\Delta\nu \quad \propto \quad nv\sigma \quad \propto \quad \frac{1}{T}\sqrt{T}\sigma. \tag{9}$$

where n is the number density, v the velocity and σ the collision cross-section. The velocity can be expressed as $v = \sqrt{2kT/m}$. The collision cross-section, σ, is related to the force law between molecules, which is of the form $1/r^m$, and the velocity. Substituting these in yields

$$\Delta\nu \propto T^{-(m+1)/2(m-1)} = T^{-\epsilon} \tag{10}$$

where $1 < m < \infty$. In the "billiard ball" case, (assuming hard sphere collisions) $m = \infty$ and $\Delta\nu \propto 1/\sqrt{T}$ while for ammonia ($m = 3$) $\Delta\nu \propto 1/T$. Note that m = 3 (a dipole) is a lower limit for a neutral gas.

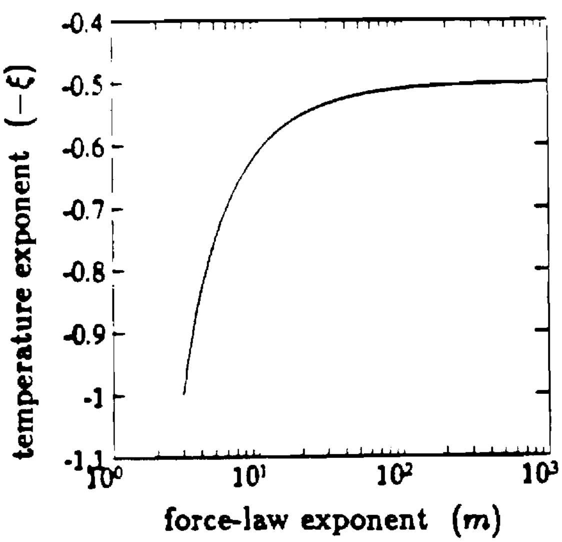

Figure 1: Temperature dependence of the line-width

The spectral line, however, is not a δ-function–it has a finite width from collisional broadening, Doppler broadening, as well as a natural width associated with the uncertainty principle. For our purposes we need consider only collisional broadening since it dominates. At the line center the line shape function should reduce to $(\pi\Delta\nu)^{-1}$. Ben-Reuven [1] derives a general line shape assuming an impact approximation, that is, the impact duration is assumed very small and effects during that time are ignored. His shape is expressed by,

$$F(\nu,\nu_o,\gamma,\varsigma,\delta)=\frac{2}{\pi}\left(\frac{\nu}{\nu_o}\right)^2\frac{(\gamma-\varsigma)\nu^2+(\gamma+\varsigma)[(\nu_o+\varsigma)^2+\gamma^2-\varsigma^2]}{[\nu^2-(\nu_o+\delta)^2-\gamma^2+\varsigma^2]^2+4\nu^2\gamma^2}\qquad 1/\mathrm{cm}^{-1} \tag{11}$$

where $\gamma = \Delta\nu$ is the line width, ς the coupling element, and δ the pressure shift term. Other line shapes can be derived using special cases of the Ben-Reuven. The commonly used Van Vleck-Weisskopf shape [4] can be used by setting $\varsigma = 0$ and $\delta = 0$, that is, no coupling or pressure shift. The Gross or kinetic shape [2] can be found by setting $\gamma = \varsigma$ and $\delta = 0$. See Waters [5] for a good discussion of this.

As a function of frequency, the absorption for collisional broadening is then

$$\alpha=\alpha_{max}\pi\Delta\nu F(\nu,\nu_o,\gamma,\varsigma,\delta)\qquad \mathrm{cm}^{-1}. \tag{12}$$

Substituting for α_{max} yields,

$$\alpha = 1.01325 \times 10^6\frac{N_oP(\mathrm{atm})}{RT}\left(\frac{T_o}{T}\right)^{\eta+1}S(T_o)e^{-(hc/k)E_l(1/T-1/T_o)}F(\nu,\nu_o,\gamma,\varsigma,\delta)\quad \mathrm{cm}^{-1} \tag{13}$$

$$= 7.34 \times 10^{21}\frac{P(\mathrm{atm})}{T_o}\left(\frac{T_o}{T}\right)^{\eta+2}S(T_o)e^{-(hc/k)E_l(1/T-1/T_o)}F(\nu,\nu_o,\gamma,\varsigma,\delta)\qquad \mathrm{cm}^{-1}. \tag{14}$$

Note that this assumes F is in $1/\mathrm{cm}^{-1}$ (i.e., all the parameters making up F are in cm^{-1}) and $\Delta\nu$ is also in cm^{-1}. This will obviously also work if all quantities are in the same unit, e.g. GHz. If $\Delta\nu$ is already in cm^{-1} but the quantities making up F are in, say GHz, then F must be multiplied by a factor of 29.9792458 in eq. (12).

2 Using Poynter and Pickett

Poynter and Pickett [3] have also compiled a database of spectral lines. Their line intensities are given in $\mathrm{nm^2MHz}$ and can be converted to cm/molecule by dividing by 2.9979×10^{18}. To get the intensity for other temperatures use eq. (1), however the units will be $\mathrm{nm^2MHz}$ and the hc in the exponent is not needed since they quote enery in "normal" energy units. One needs to just make sure to use the proper form for Boltzmann's constant. Other conversions are also needed since they use pressure in torr and line widths in MHz. To get α_{max} using their catalog one must keep these conversions in mind. Beginning with eq. (3) and using Poynter and Pickett's intensity in $\mathrm{nm^2MHz}$ yields

$$\alpha_{max}=\frac{1}{\pi 2.9979 \times 10^{18}}\frac{n(\mathrm{molecule/cm^3})S(\mathrm{nm^2MHz})}{\Delta\nu(\mathrm{cm^{-1}})}\quad \mathrm{cm}^{-1}. \tag{15}$$

The ideal gas law (4) can be written

$$n = 3.21933 \times 10^{16}P(\mathrm{torr})\left(\frac{300}{T(K)}\right)\qquad \mathrm{molecule/cm^3} \tag{16}$$

Also, $\Delta\nu(\mathrm{cm^{-1}}) = 1/29979\ \Delta\nu(\mathrm{MHz})$. Substituting these in yields

$$\alpha_{max}=102.47P(\mathrm{torr})\frac{S(\mathrm{nm^2MHz})}{\Delta\nu(\mathrm{MHz})}\left(\frac{300}{T(K)}\right)\quad \mathrm{cm}^{-1}. \tag{17}$$

One can then use eq. (12) to get the opacity as a function of frequency.

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PPENDIX E: To be presented at the 25th Annual Meeting of the Division for lanetary Sciences of the American Astronomical Society, Boulder, CO, ctober 18-22, 1993.

tmospheric Profiles and Sulfuric Acid Vapor (H2SO4) Profiles from the ctober 1991 Magellan Orbiter Radio Occultation Experiments at Venus

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n October 5 and 6, 1991, dual-frequency radio occultation measurements of the enus atmosphere were conducted on three successive orbits using the elecommunications system aboard the Magellan spacecraft and the 70 meter DSN ntenna at Tidbinbilla, Australia. The experiments probed between 56 and 68 egrees N latitude and a solar zenith angle of approximately 112 degrees. The igh radiated power (EIRP) from the spacecraft, plus the accurate pointing of he spacecraft antenna, made it possible to develop highly accurate profiles f atmospheric refractivity and absorptivity down to the 36 km level at .6 cm, and down to the 34 km level at 13 cm (above a mean radius of 6052 km). he refractivity profiles have yielded vertical profiles of temperature and ressure in the neutral atmosphere, while the combination of refractivity and bsorptivity profiles have yielded profiles of H2SO4(g). The data sets have een processed using a recently developed technique for finding a unique olution to the 2-way radio occultation problem. The analysis of the data sets ncludes error bars derived using the Standard Propagation of Errors. The emperature and pressure profiles are compared to the Pioneer Venus probe easurements and the VIRA model. The three sets of profiles are compared to nvestigate atmospheric variability over the spatial scales spanned between ccultations (the atmosphere rotated between 6 and 12 degrees between uccessive orbits.)

APPENDIX F: PREPRINT OF:

Radio Occultation Studies of the Venus Atmosphere with the Magellan Spacecraft. 1. Experiment Description and Performance

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ABSTRACT

While primarily designed for radar studies of the Venus surface, the high radiated power (EIRP) from the Magellan spacecraft makes it an ideal transmitter for use in radio occultation measurements of the refractivity and absorptivity of the Venus atmosphere. Such experiments have been conducted involving transmissions at 2.3 GHz and 8.4 GHz (13 cm and 3.6 cm, respectively), during spacecraft ingress. Since the stability of the spacecraft transmitter is critical for accurately determining the doppler shift and amplitude attenuation created as the ray penetrates the atmosphere, the spacecraft transmitter was locked to a 2.1 GHz uplink from a 70-meter DSN station which also received the signals. Because of the high directivity of the spacecraft antenna, and the significant ray bending in the deep Venus atmosphere, a spacecraft tracking maneuver was designed to keep the spacecraft antenna pointed in the direction of the refracted ray path back to earth. This tracking maneuver, plus the high effective isotropic radiated power (EIRP) of the Magellan transmitter has yielded 3.6 cm refractivity and absorptivity profiles down to the 35 km altitude and 13 cm profiles down to the altitude of critical refraction (approximately 33 km). The statistical uncertainties in the derived profiles are significantly lower than those previously obtained, resulting in extremely accurate profiles of H_2SO_4 (g) abundance, as discussed in an accompanying paper by Jenkins et al. (1993).

I. INTRODUCTION

Recent studies of the nature and variability of the 13 cm-wavelength opacity of the Venus atmosphere measured by Pioneer Venus radio occultation experiments (Jenkins and Steffes, 1991) have indicated significant temporal and spatial variations in the abundance of gaseous H_2SO_4 (the predominant 13 cm absorber) below the main cloud layer. However, the ability of such radio occultation experiments to accurately determine the microwave opacity and refractivity of the deep Venus atmosphere was limited by the relatively low signal-to-noise ratio achievable when transmitting back to the earth through the highly absorptive and refractive atmosphere. Such low signal-to-noise ratios were partially due to the relatively low antenna gains and transmitted powers of previous spacecraft, and by the limited ability to keep the spacecraft antennas oriented toward the actual ray path to earth in the presence of significant time-variable ray bending in the Venus atmosphere.

For example, the Pioneer Venus orbiter was equipped with a 20 watt S-Band (13 cm) transmitter. However, due to the degradation of the solar cell panels, 13 cm transmitted power levels of only 10 watts were maintained for most of the mission. The result was an EIRP (Effective Isotropic Radiated Power, or the product of transmitted power and antenna gain) of on only 33.1 dBw, or 2040 watts. Because antenna limb-tracking maneuvers were only conducted for a limited number of orbits, the actual EIRP radiated toward earth at the deepest level of most Pioneer Venus radio occultations was only 30 1 dBw, or 1020 watts. By comparison, the Magellan spacecraft, with its large antenna (3.7 meter diameter) radiates an EIRP of 44 dBw, or 25,120 watts, and is thus able to maintain a measurable signal at an earth receiving station in the presence of substantial absorption and refractive defocussing in the deep Venus atmosphere. At X-Band (3.6 cm) the comparison of spacecraft EIRP is even more striking (26.1 dBw, or 410 watts for Pioneer Venus versus 61.4 dBw or 1,380,000 watts for Magellan). Moreover, because of the design of the Magellan spacecraft (3-axis stabilized, with high pointing accuracy), we have developed limb tracking maneuvers which maintain spacecraft antenna pointing to within about 0.4 degrees of the actual refracted ray path back to earth, and have determined actual spacecraft attitude to within an accuracy of better than 0.1 degrees.

From this discussion it is clear that use of the Magellan spacecraft for radio occultation experiments can allow development of far more accurate absorptivity profiles for the Venus atmosphere (due to higher signal-to-noise ratios and accurate antenna pointing), both at 13 cm and at 3.6 cm. Moreover, the increased signal levels allow penetration to a much deeper level in the Venus atmosphere, as shown in Table 1. Since the deepest level sensible by a radio occultation experiment is determined by the altitude at which critical refraction occurs (approximately 32.8 km, relative to a mean radius of 6052 km) Magellan radio occultation experiments allow nearly complete access to the complete sensible altitude range, and orbital precession provides many opportunities to probe over wide ranges of latitude and longitude.

II. DESIGN OF THE EXPERIMENT

As shown in Figure 1, the radio occultation occurs when the earth is occulted by the Venus atmosphere, as viewed by the spacecraft. More complete descriptions of the theoretical bases for this technique are given in Fjeldbo et al. (1971), Eshleman (1973), and Jenkins and Steffes (1991). In this experiment, the spacecraft modulation is switched off and continuous wave (CW) signals are transmitted by the spacecraft during the occultation event at 2.298 GHz (S-Band, or 13 cm) and at 8.425 GHz (X-Band, or 3.6 cm). The signals are received at a 70-meter diameter antenna at one of the three NASA Deep Space Network (DSN) facilities (Goldstone, California; Madrid, Spain; or Tidbinbilla, Australia). The large receiving antennas are necessary to make accurate estimates of the amplitude and frequency of the received signals in the presence of substantial attenuation and defocussing in the Venus atmosphere. Likewise, radio occultation measurements are scheduled as close as possible to inferior conjunction so that the received signal levels will be as large as possible, further improving the accuracy of the measurement.

In order to accurately determine the effects of the atmosphere on the amplitude and frequency of the radiated signals, these signals must be stable in both amplitude and frequency when transmitted by the spacecraft. To ensure the frequency is stable, a reference signal (2.116 GHz) is uplinked to the spacecraft by the same 70 meter DSN station. High transmitter power is used (80 kilowatts) so as to assure that the reference signal will be detectable by the spacecraft for the full duration of the experiment. The spacecraft oscillator is locked to this signal and downlinks two non-integer harmonics of the received frequency. The power output of the spacecraft is stabilized internally. The occultation experiment begins when the path of the signal transmitted by the spacecraft tangentially grazes the edge of the atmosphere of Venus. As the spacecraft's trajectory carries it toward the limb of the planet, the path of the signal slices deeper into the atmosphere, traversing a longer pathlength through the limb. Refraction in the atmosphere causes the signal to bend around the limb of the planet. This increases the Doppler shift since a larger component of the velocity of the spacecraft is now parallel to the ray path back to Earth. It is important to note that this also affects the uplinked reference signal from Earth. Hence the Doppler shift of the signal received at Earth includes the shift incurred by the uplink to the spacecraft as well as that by the downlink. Because the spacecraft transmitter is locked to the uplinked reference signal, it is generally more practical to conduct this experiment as the spacecraft enters occultation, also referred to as an "ingress" occultation.

The magnitudes of the doppler shifts which occur during a radio occultation experiment are substantial, and must be anticipated before the experiment is conducted. For example, changes in the received frequencies on uplink and downlink due to spacecraft orbital motion alone can be as much as 75 kHz during a radio occultation experiment. Ray bending in the atmosphere can result in an additional 40 kHz (at 3.6 cm) of doppler shift during the experiment. The bandwidth of the receiving system required to support such substantial frequency variations (over 200 kHz) and the resulting large amount of data which would need to be stored (over 3.2 MBits/second for each of the received channels assuming 8-bit sampling) becomes impractical. However, because the trajectory of the Magellan spacecraft is very well known and monitored, and because the general nature of the refractivity of the Venus atmosphere is well understood, it is possible to predict to accuracies of better than 10 kHz the actual doppler shifts to be encountered. (A radio occultation experiment simulator has been developed for this purpose, and is described in

Section III.) Thus, for these experiments, the uplink transmitter frequency was pre-programmed to correct for expected uplink doppler effects and the ground station receiver frequency was likewise pre-programmed to account for downlink doppler effects. The passband in which the downlink signal was recorded was therefore reduce to 20 kHz for both 3.6 cm (8.425 GHz) and 13 cm (2.298 GHz) and the stored data was reduced to 400 kilobits per second of experiment duration. (Magellan radio occultation experiments can run from about 8 minutes for a periapsis occultation to 25 minutes for an apoapsis occultation.)

The power of the received signal is reduced by two atmospheric effects and by mispointing of the spacecraft antenna. First, the curvature of the atmosphere and the changing refractive index profile cause spreading of the transmitted beam, an effect known as refractive defocussing. Second, absorption and scattering in the atmosphere extract energy from the signal, causing an additional drop in received power. In addition, as the ray is bent by refraction in the atmosphere, it is also bent away from the main axis of the spacecraft antenna, causing a drop in power due to the smaller off-axis gain of the antenna. Because of the high directivity of the Magellan antenna (the half-power beamwidth is only 2.3 degrees at 13 cm and 0.57 degrees at 3.6 cm) and the substantial ray bending which occurs in the Venus atmosphere (over 15 degrees at the deepest level probed), a spacecraft attitude adjustment, or limb-tracking maneuver must be designed to keep the antenna oriented toward the ray path back to earth. Moreover, precise determination of pointing error is essential for correcting amplitude variations due to antenna mispointing and assuring that such variations are not interpreted as atmospheric effects. A ray-tracing computer program which computes both doppler shifts and ray bending has been described in Section III.

Besides measuring the amplitudes and frequencies of the two downlinked signals, it is also possible to measure their polarization. No such measurements have been made during previous experiments since the relatively low signal-to-noise ratios made it impossible to measure any component in the orthogonal polarization, and because of limited data storage facilities. The Magellan spacecraft transmits a linearly polarized signal at 13 cm, and a right-hand circularly polarized signal at 3.6 cm. The receiving system at the NASA-DSN 70 meter antennas receives right-hand circular and left-hand circular polarizations at both wavelengths. As a result it is not possible to directly measure cross polarization discrimination at 13 cm. It is possible to infer the polarization isolation by post processing the S-Band data, but we have instead chosen to process the two S-Band data streams independently, since both will receive half of the downlink wave power, and the noise in the two orthogonal channels is statistically independent. Thus, it is possible to confirm the relative magnitude of the statistical uncertainty in the derived profiles by independently processing data from these two channels. At 3.6 cm (X-Band), the signal in the orthogonal polarization (left circular polarization) can be directly measured. In fact, because the cross polarization discrimination of the Magellan X-Band transmitting antenna is only about 34 dB, it is possible to directly detect the orthogonally polarized signal in the absence of other atmospheric attenuation. It should be noted that abrupt depolarization of coherent, centimeter-wavelength signals occurs in the earth's atmosphere in the presence of lightning (Furuta et al., 1985). Thus, similar detection of lightning in the clouds of Venus may be possible, but none has yet been found.

III. RADIO OCCULTATION EXPERIMENT SIMULATION

A powerful tool for planning Venus radio occultation experiments is a program called OccSim which simulates the occultation experiment. Given a spacecraft trajectory data file, Earth and Venus ephemerides, atmospheric absorptivity and refractivity profiles (for Venus), it generates predictions for received power, Doppler shift, and ray bending as time-series (Ref, Jenkins, 1992).

Let the absorptivity $\alpha(r)$ and index of refraction $n(r)$ be specified at radii $r_o > r_1 > ... > r_m \geq 6052$ km (the mean radius of Venus). $\alpha(r)$ can be estimated by averaging and extrapolating previous radio occultation absorptivity profiles (Jenkins and Steffes, 1991). $n(r)$ can be estimated using the atmospheric density profiles determined by the Pioneer Venus probes (Seiff et al., 1980) and by using laboratory results for the refractivity of CO_2 and N_2 (Essen and Froome, 1951). Let $n_o = n(r_o) = 1$, and $n(r) = 1$ for $r > r_o$. Let t_j, $j = 1,...,N$ be the points in time that we wish to generate received power p_j and Doppler residuals f_{rj}. OccSim generates synthetic radio occultation data in two steps.

Referring to Figure 2, the ray path parameters δ_i (bending angle) and a_i (ray impact parameter), and the excess attenuation τ_i are determined for rays with periapses r_i, $i = 1,...,M$. Consider a ray with impact parameter $a_i = n_i r_i$ provided that there is no radius $r>r_i$ with $n(r) = ra_i$. The bending angle δ_i for each ray must be found by tracing the ray through the model atmosphere. The trajectory of a ray traveling in a medium whose index of refraction depends only on radius is given by

$$\theta(r) = \int_{r_o}^{r} \frac{a_i dr'}{r\sqrt{a^2(r') - a_i^2}} \tag{1}$$

where (r,θ) are the polar coordinates of the trajectory ($\theta = 0$ radians at $r = r_o$). (Ref. Born and Wolf, 1980). The bending angle δ_i is related to the angle of incidence ψ_i of the ray at the top of the atmosphere and the angle $\theta(r_i)$ that the ray traverses as it travels from r_o to r_i by $\delta_i = 2[\psi_i + \theta(r_i)] - \pi$. The excess attenuation is simply the ray path integrated absorptivity, and is found by evaluating

$$\tau(r) = 2\int_{r}^{r_o} \frac{\alpha(r')a(r')dr'}{\sqrt{a^2(r') - a^2(r)}} \tag{2}$$

at $r = r_i$. To implement equations (1) and (2) numerically, the absorptivity profile $\alpha(r)$ and the ray impact parameter $a(r)$ are modeled as continuous piecewise linear functions (this corresponds to $n(r)/r$ being piecewise linear). In this case, closed form expressions exist for both integrals.

In the second step, OccSim uses the spacecraft trajectory data and planetary ephemerides to construct the occultation geometries for the uplink and downlink legs of the ray received at Earth at each time t_j, $j = 1,...,N$. The tables δ_i, τ_i generated in the first step are interpolated to find the ray path parameters for the uplink and downlink legs, and the excess attenuation experienced by the downlink ray received at time t_j. The excess Doppler shift and refractive defocussing can be calculated from the ray path parameters and the occultation geometry as per Jenkins and Steffes

(1991).

Thus, by using OccSim it is possible to predict refractive defocussing, absorption, and Doppler shifts which will occur due both to spacecraft motion and atmospheric ray bending. It is also possible to predict the actual ray trajectory (in J2000 vector coordinates) back to earth. The predicted doppler shifts are used in programming the uplink transmitter and downlink receiver frequency settings, and the ray path direction is used in developing the limb-tracking maneuver for keeping the spacecraft antenna properly oriented.

IV. LIMB-TRACKING MANEUVER

Once pointing vectors for the desired antenna directions are computed, a limb-tracking maneuver which adjusts the spacecraft attitude so as to keep the antenna optimally pointed during the extent of the radio occultation experiment must be designed. These maneuvers may vary drastically in their magnitude and rate of motion depending on the nature of the orbital trajectory during the experiment.

For the three radio occultation experiments conducted in October 1991, relatively short limb tracking maneuvers were required (approximately 3 minutes) because the spacecraft was near orbital periapsis during the occultation. Fortunately, the motion of the spacecraft antenna pointing vectors formed a conic surface. Thus, a "conic turn" was developed which would always keep the spacecraft oriented within 0.1 degrees of the projected earth ray path direction.

(See Figure 3.) Turning rates of up to 0.12 degrees per second were required. The actual pointing accuracy achieved depends on the variations in the Venus atmosphere from the model atmosphere, but can be accurately determined once the actual ray path geometry is reconstructed from doppler data and spacecraft trajectory information. In Figure 4, we show the actual pointing accuracy achieved during an occultation experiment conducted during Magellan orbit #3212 (October 5, 1991). Note that the maximum error was only 0.4 degrees, determined to an accuracy of ± 0.08 degrees. For occultations occurring when the spacecraft is nearer to orbital apoapsis (e.g. December 1992), the duration of the maneuver is significantly longer (over 15 minutes). Since the required spacecraft antenna pointing vectors for such occultations cannot be tracked by simple spacecraft turns, the pointing control system originally used for the radar mapping system has been employed. Referred to as the RQPC (Radioscience Quaternian Polynomial Coefficients) system, an eighth order polynomial is used to approximate the desired pointing profile (Lyons, 1992). The polynomial coefficients and execute times are uploaded to the spacecraft which then executes the maneuver. This approach was used during 4 successful radio occultation experiments conducted in December 1992, and while specific results are not yet available, it appears as if tracking accuracies of better than 0.5 degrees are readily achievable, with measured uncertainties of less than 0.1 degrees.

V. PERFORMANCE AND RESULTS

To date, seven radio occultation experiments with full limb tracking maneuvers have been conducted (three in October 1991 and four in December 1992). In addition, occultation data has also been taken when no limb tracking maneuvers were conducted, but probed only down to about 65 km. Specific results for the October 1991 experiment are presented in the accompanying paper by Jenkins et al. (1993), but highly accurate profiles of atmospheric absorptivity and refractivity have been obtained down to 35 km altitude at X-Band (3.6 cm) and to 33 km at S-Band (13 cm). The refractive profiles have been used in developing profiles of atmospheric temperature and to detect gravity-damped buoyancy waves in the Venus troposphere. While the X-Band and S-Band refractivity profiles are nearly identical for the neutral atmosphere, they are significantly different in the ionospheric regions (above 100 km). Thus, the differential refractivity profiles can be used in characterizing the structure and dynamics of the ionosphere. The absorptivity profiles have provided very accurate abundance profiles for gaseous H_2SO_4, the major source of microwave opacity immediately below the Venus cloud layers. Moreover, because 3.6 cm absorptivity profiles have been obtained for the first time to relatively deep levels, it has been possible to confirm gaseous H_2SO_4 as the major source of this microwave opacity (based on the frequency dependence of the absorption). Likewise, the accuracy of the gaseous H_2SO_4 abundance profiles obtained are significantly improved since the magnitude of the absorption is significantly larger at the 3.6 cm wavelength.

Since the radio occultation technique measures atmospheric properties in a relatively localized area, it has been shown to be useful for characterizing latitudinal variations in constituent abundance and atmospheric structure. (See, for example, Jenkins and Steffes, 1991). The October 1991 Magellan radio occultation experiments probed the middle northern latitudes on the night side of the planet (latitudes around 57 degrees north, and solar zenith angles around 114 degrees), a zone which had been measured coarsely by previous Pioneer Venus radio occultations. However, the first two Magellan radio occultations conducted in December 1992 probed near the south pole at the terminator (approximately 88 degrees south latitude and 92 degrees solar zenith angle), and the latter two probed mid-southern latitudes on the day side (approximately 50 degrees south latitude and 55 degrees solar zenith angle). This is significant in that the Pioneer Venus orbiter radio occultation measurements provided almost no coverage of the southern hemisphere (at altitudes below 65 km). Also of note is that the latter two radio occultation experiments (conducted December 20, 1992) were conducted when the orbital geometry resulted in what is known as a "grazing" occultation. As a result, the deepest altitude probed was only 35 km (versus 33 km for the earlier experiments). However, since the contact was never lost with the spacecraft, it was possible to take data both during spacecraft ingress and egress, providing a wider range of locations probed. Reduction of the data from the December 1992 experiments is ongoing, and will be reported at a future date.

VI. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

The Magellan spacecraft is an ideal vehicle for conducting radio occultation studies of the atmosphere and ionosphere of Venus. The highly accurate profiles of microwave refractivity and absorptivity developed by these experiments, and the ability to characterize wave depolarization, are key products in monitoring atmospheric and ionospheric structure and dynamics. From these products, profiles of ionospheric density, atmospheric pressure and temperature, sulfuric acid vapor abundance, and atmospheric buoyancy waves can be developed. The successful demonstration of highly accurate limb tracking maneuvers and the resulting high signal-to-noise ratios have provided these profiles with higher accuracies and to lower depths in the Venus atmosphere than achieved by any previous mission. With the completion of the radar mapping portion of the Magellan mission, and the initiation of gravity field studies, the advanced spacecraft attitude control system (RQPC system) has available for radio occultation limb tracking maneuvers, which can provide accurate monitoring of the deep Venus atmosphere for the remainder of this decade. Given that Magellan will be the last mission to Venus of this century, its importance in providing this information will be crucial.

ACKNOWLEDGEMENTS

The authors wish to extend their most heartfelt thanks to the Magellan Project for conducting these experiments and making the data available to the community. We note especially the efforts of Project Scientist - R.S. Saunders, Project Manager - D.G. Griffith, Project Engineer - D. Okerson, and most especially Science Manager - T.W. Thompson. We are deeply grateful to the many JPL project personnel and the JPL Multimission Radioscience Support Team who helped in this effort including A. Devereaux, G.M. Gonzales, A. Horton, A. Nakata, and the Deep Space Network operators. Authors RSA, SWA, DTL, and EHS were supported for data collection by the Magellan Project which is operated by the Jet Propulsion Laboratory, California Institute of Technology under contract from the National Aeronautics and Space Administration. PGS was supported by Grant NAGW-533 from the NASA Planetary Atmospheres Program, as was JMJ prior to April, 1992. Subsequently, JMJ has been supported by Grant NCC2-753 from NASA Ames Research Center, Pioneer Venus Guest Investigator Program. GLT was supported by NASA under contract JPL 957089 from the Magellan Project.

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TABLE I:

OCCULTATION EXPERIMENTS AT VENUS

YEAR	SPACECRAFT	WAVELENGTH	DEPTH PROBED
1967	Mariner 5[1]	70 cm	~35 KM
		13 cm	~35 KM
1974	Mariner 10[2]	13 cm	~38 KM
		3.6 cm	~48 KM
1975	Venera 9 and 10[3]	32 cm	~40 KM
1978-1992	Pioneer Venus[4]	13 cm	~38 KM
	Orbiter	3.6 cm	~47 KM
1984	Venera 15 and 16[5]	32 cm	~42 KM
		5 cm	~46 KM
1991 -	Magellan	13 cm	~33 KM
		3.6 cm	~35 KM

1. Fjeldbo et al., 1971
2. Howard et al., 1974
3. Yakovlev et al., 1976
4. Cimino et al., 1978; Jenkins and Steffes, 1991
5. Yakovlev et al., 1987; Matyugov et al., 1990

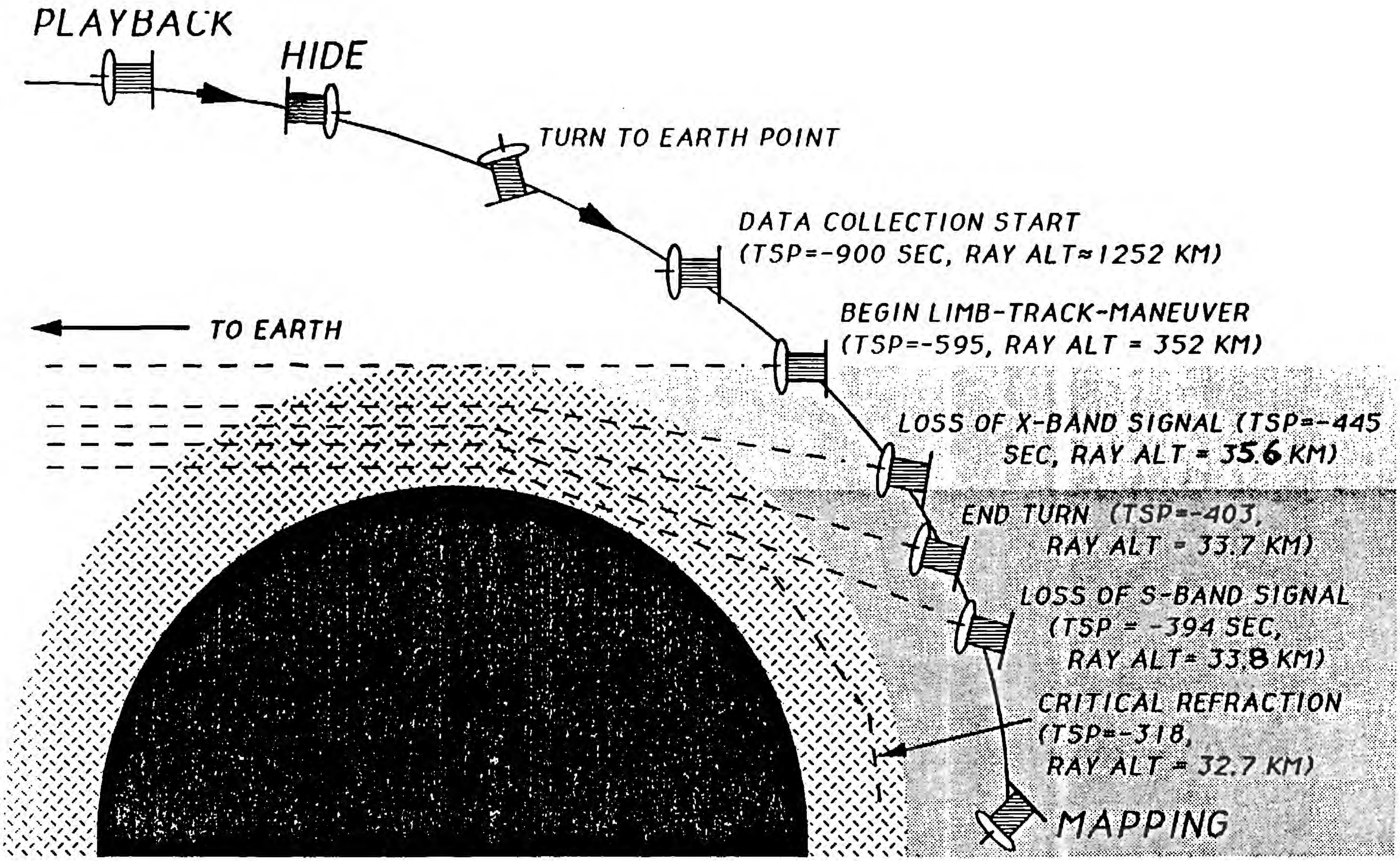
FIGURE CAPTIONS

Figure 1. Typical profile of Magellan radio occultation experiment studying the Venus atmosphere.

Figure 2. Occultation experiment geometry. The geometry is shown for one leg of a two-way radio occultation experiment.

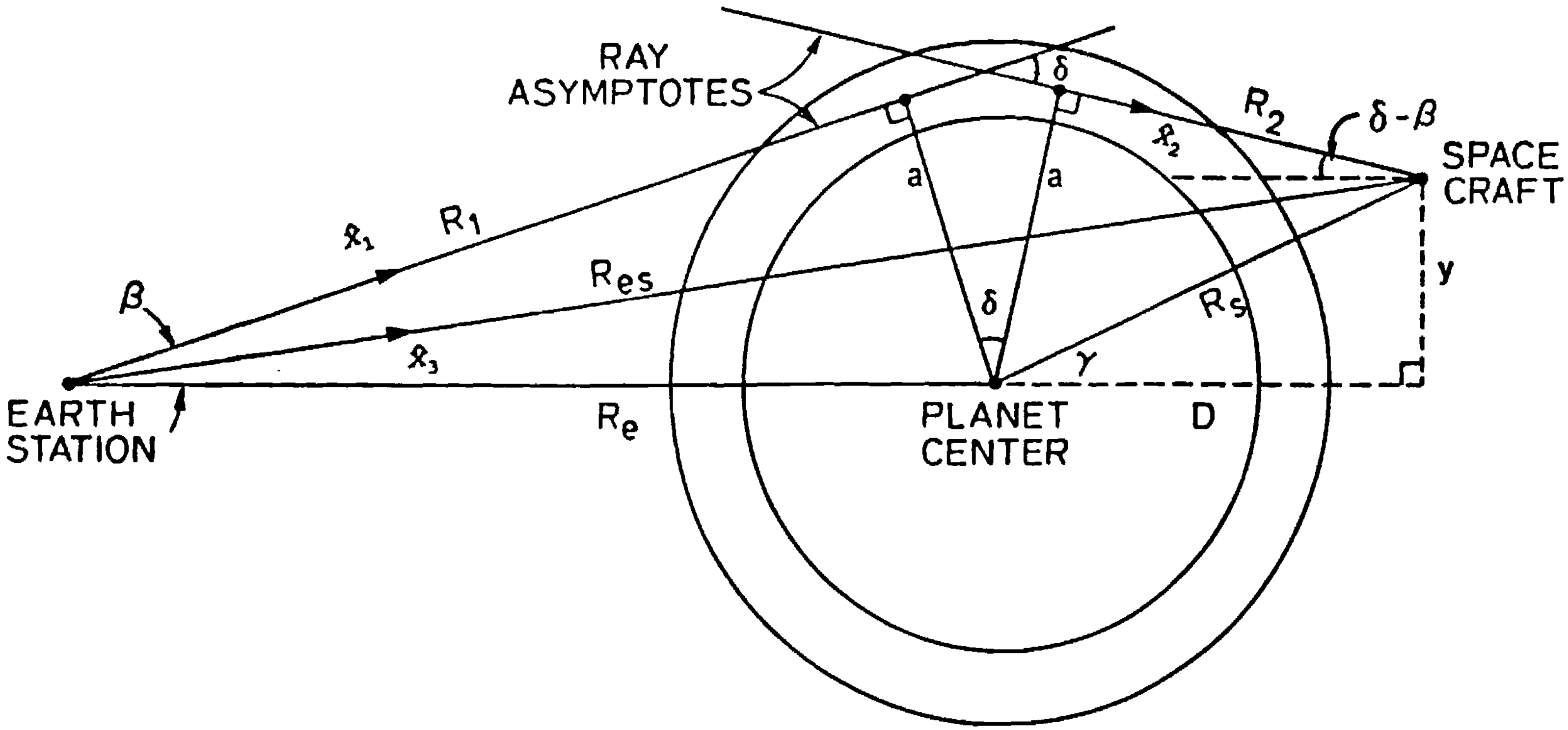
Figure 3. Predicted pointing error for October 5 limb tracking maneuver, based on the predicted ray bending in the model atmosphere.

Figure 4. Actual performance of antenna pointing maneuver relative to actual ray path direction to earth determined from occultation data and spacecraft telemetry.



PLAYBACK
HIDE
TURN TO EARTH POINT
DATA COLLECTION START
(TSP=-900 SEC, RAY ALT≈1252 KM)
TO EARTH
BEGIN LIMB-TRACK-MANEUVER
(TSP=-595, RAY ALT = 352 KM)
LOSS OF X-BAND SIGNAL (TSP=-445 SEC, RAY ALT = 35.6 KM)
END TURN (TSP=-403, RAY ALT = 33.7 KM)
LOSS OF S-BAND SIGNAL (TSP = -394 SEC, RAY ALT= 33.8 KM)
CRITICAL REFRACTION (TSP=-318, RAY ALT = 32.7 KM)
MAPPING

Figure 1



RAY
ASYMPTOTES
δ
R_2
δ - β
SPACE
CRAFT
ℓ_2
a
a
ℓ_1
R_1
R_{es}
β
δ
R_s
y
ℓ_3
γ
EARTH
STATION
R_e
PLANET
CENTER
D

Figure 2

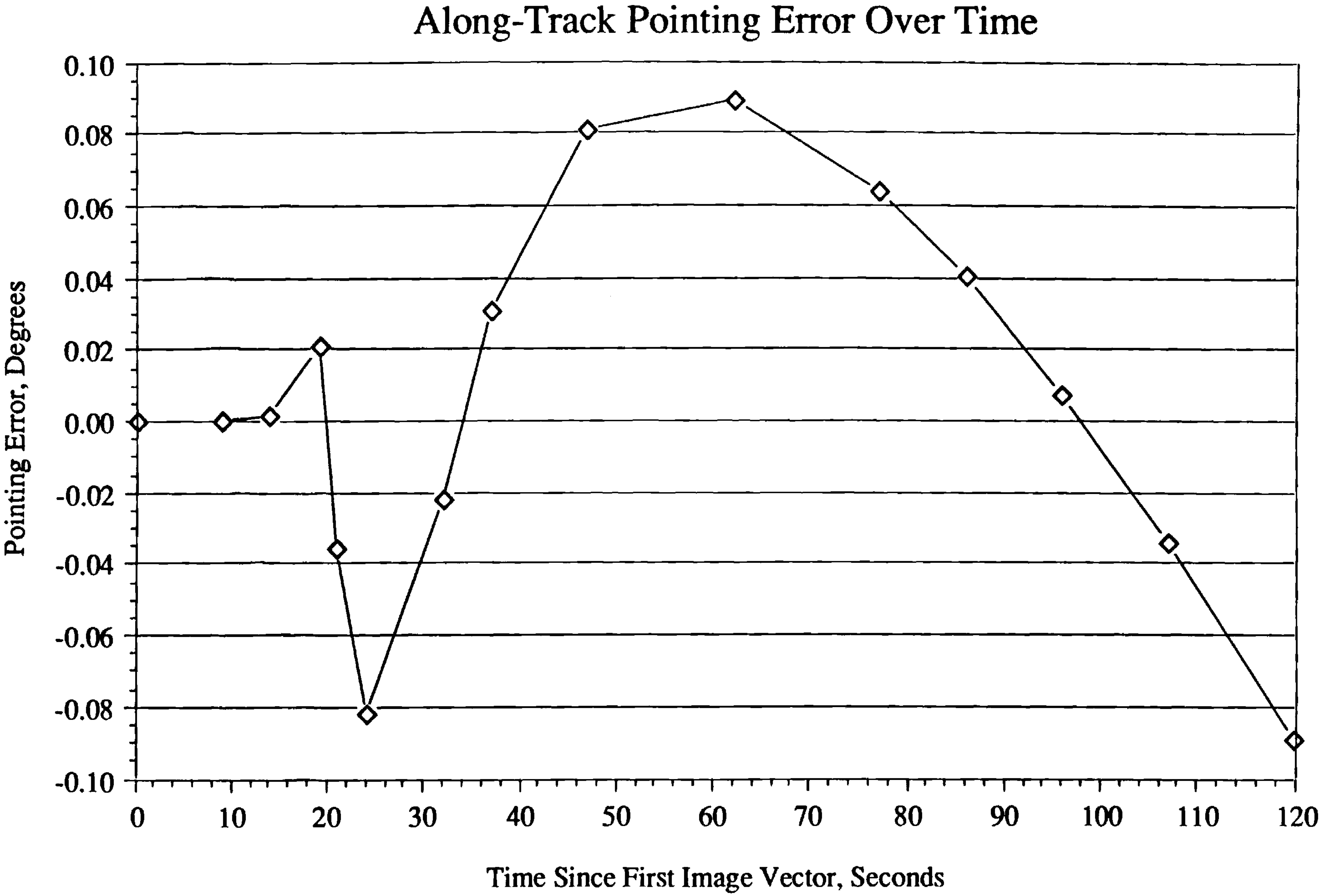

Along-Track Pointing Error Over Time
Pointing Error, Degrees
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
0
10
20
30
40
50
60
70
80
90
100
110
120
Time Since First Image Vector, Seconds

Figure 3

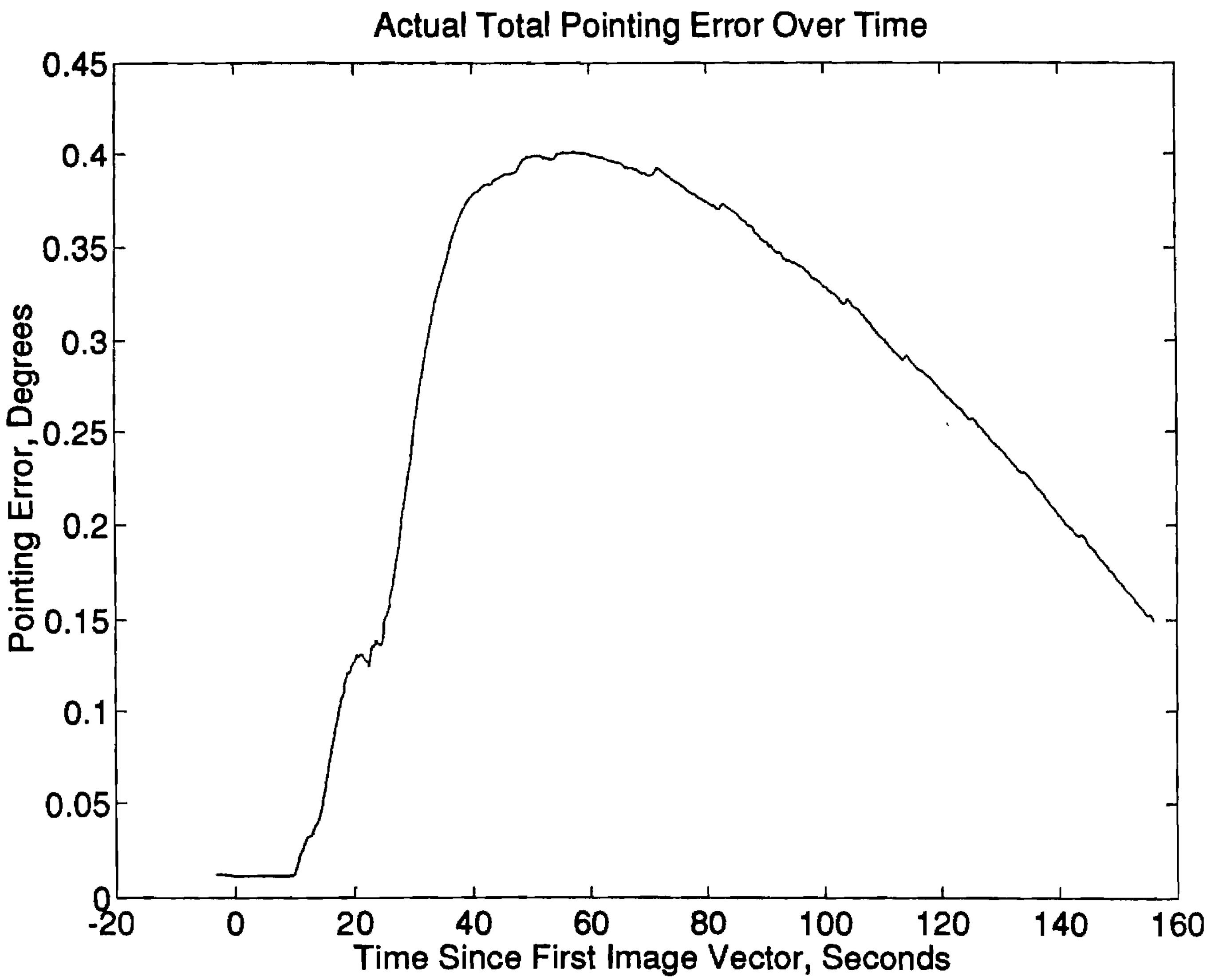

Actual Total Pointing Error Over Time
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Pointing Error, Degrees
-20
0
20
40
60
80
100
120
140
160
Time Since First Image Vector, Seconds

Figure 4

E-21-643
20

GEORGIA TECH RESEARCH CORPORATION

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
PROGRAM INITIATION DIVISION
ATLANTA, GEORGIA 30332-0420
USA

Telex: 542507 GTRC OCA ATL
Fax: (404) 894-6956

Phone: (404) 894-4817

Refer to: JG/02.105.002.95.002
E-21-643

12 July 1994

Ms. Barbara Cephas, Grants Officer
Code HWG
NASA Headquarters
Washington, D.C. 20546

Subject: Research Proposal Entitled, "Laboratory Evaluation and Application of Microwave Absorption Properties under Simulated Conditions for Planetary Atmospheres"

Reference: Grant No. NAGW-533

Dear Ms. Cephas:

The GEORGIA TECH RESEARCH CORPORATION desires to submit for your consideration the subject proposal prepared by Dr. Paul G. Steffes, School of Electrical and Computer Engineering, Georgia Institute of Technology.

A description of the research program, the time required and program cost are included in the proposal. Should additional information be desired, please do not hesitate to contact Dr. Steffes at 404/894-3128 regarding technical matters or the undersigned at 404/894-4817 for administrative concerns.

In the event of an award, we propose that the work be authorized by a supplement to the referenced grant.

We appreciate the opportunity of submitting this proposal and look forward to working with you on this project.

Sincerely,

Janis L. Goddard
Contracting Officer

JLG/kgw

Addressee: One copy
Enclosure: Proposal - One copy

cc: Dr. Jay T. Bergstralh
Code SLC

PLANETARY ASTRONOMY AND ATMOSPHERES PROGRAMS

Log No.	
Date Received:	

Do not write in the shaded area.

NRA #: NRA 94-055-01 **Grant/Contract/RTOP #:** NAGW-533

Date Submitted: July 8, 1994

Please check all boxes appropriate to this NRA:

☐ Planetary Astronomy ☒ Planetary Atmospheres ☐ Major Equipment ☒ Education Request ☐ Computer Request

☐ Full Proposal: New Research ☐ Full Proposal: Renew Ongoing Research ☒ Progress Proposal

Research Area: Laboratory Measurements: Microwave and Millimeter-wave
(Indicate main research area; i.e., inner planets, outer planets, comets, satellites, etc.)

Type of Organization: University
(Profit, non-profit, university, etc.)

Proposal Title: Laboratory Evaluation and Application of Microwave Absorption Properties under Simulated Conditions for Planetary Atmospheres

Principal Investigator (Name): Paul G. Steffes (Professor)

Institution: Georgia Institute of Technology

Address: School of Electrical and Computer Engineering

City/State/Zip Code: Atlanta, GA 30332-0250

Telephone: (404) 894-3128 **Fax:** (404) 853-9171

E-Mail Address: ps11@prism.gatech.edu

Signature: [signature] Date: July 8, 1994

Institutional Authorization Official: Janis L. Goddard

Signature: [signature] Date: 7/12/94

Address: Georgia Tech Research Corporation/OCA-PID

City/State/Zip Code: Atlanta, GA 30332-0420

Telephone: (404) 894-4817 **Fax:** (404) 894-6956

B. COGNIZANT PERSONNEL

For scientific or technical matters relating to the grant (Principal Investigator):

Paul G. Steffes
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0250
Telephone: (404) 894-3128
email: ps11@prism.gatech.edu

For contractual and business matters:

Georgia Tech Research Corporation
ATTN: Janis L. Goddard
Georgia Institute of Technology
Atlanta, GA 30332- 0420
Telephone: (404) 894-4817
Fax: (404) 894-6956

(There are no Co-Investigators for this Grant.)

Proposed Project Duration: 12 months

Start date: November 1, 1994

End date: October 31, 1995

Budget Request: $67,624 (This is for the third year of a 3-year project.)

Supplemental Budget Request: $35,000 (Educational Research Activities, See Appendix E)

C. PROPOSAL SUMMARY

TITLE: Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres

PRINCIPAL INVESTIGATOR: Paul G. Steffes (Georgia Institute of Technology)

ABSTRACT

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave and millimeter-wave absorbing constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements and to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profile of constituents in those planetary atmospheres.

Key accomplishments achieved in the currently completed grant year include:

1. Completion of laboratory measurement of the microwave opacity and refraction from H_2S under simulated conditions for the outer planets, and development of a new formalism for the microwave opacity and refractivity of H_2S. (DeBoer and Steffes, 1994a).

2. Development of an upgraded, computer-based microwave, laboratory measurement system to reduce uncertainties in measured opacities.

3. Assisted in the planning and conduct of 10 Magellan-Venus radio occultation measurements conducted in June-August 1994.

4. Began laboratory measurement of the temperature dependence of the opacity from SO_2 at 1.3, 3.6, and 13 cm at temperatures from 365 K to 500 K and at pressures from 1-4 Bars in a CO_2 atmosphere.

Key activities planned for the next grant year include:

1. Application of the results for H_2S to the Voyager 2 radio occultation data so as to estimate limits on its abundance and distribution in the atmosphere of Neptune.

2. Completion of laboratory measurements of the opacity from SO_2 under Venus conditions, and development of a formalism with greater accuracy ($\pm$10%).

3. Develop a new laboratory experiment to more accurately characterize the 13 cm and 3.6 cm opacity of gaseous H_2SO_4.

D. BUDGET SUMMARY (Grant #NAGW-533)

PRINCIPAL INVESTIGATOR: Paul G. Steffes

TITLE: Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres

GRANT NUMBER: NAGW-533
For the period of November 1, 1994 through
October 31, 1995(Third year of 3-year program)

ESTIMATED COST BREAKDOWN

I.	DIRECT SALARIES AND WAGES*:		$39,621
	A. Principal Investigator P.G. Steffes 24% time, calendar year (.24 person-years)	$21,670	
	B. 1 Graduate Student (D.R. DeBoer) 50% time, calendar year (.5 person-years)	$15,000	
	C. 1 Sr. Admin. Secretary 12% time, calendar year (.12 person-years)	$ 2,951	
II.	FRINGE BENEFITS**: 24.7% of Direct Salaries & Wages (less students)		$ 6,082
III.	MATERIALS, SUPPLIES, AND SERVICES		$ 1,300
	A. Gases, liquids and supplies for Experiments	$ 700	
	B. Miscellaneous Project Supplies and page charges	$ 600	
IV.	TRAVEL		$ 1,300
	A. Travel for Student to AAS/DPS Meeting (Kona, HI, 6 days duration, airfare $600 plus registration and $100/day)	$ 1,300	
	SUBTOTAL - ESTIMATE OF DIRECT COSTS:		$48,303
V.	OVERHEAD (Indirect Expense)**: 40% of Modified Total Direct Cost Base		$19,321
	TOTAL BUDGET (12 months) REQUESTED FROM NASA:		$67,624

ESTIMATED TOTALS TO COMPLETION OF RESEARCH:
Funds: $67,624 Months: 12

(Note: Supplemental Budget Request attached as Appendix).
*The salary and wage rates are based on FY 95 salaries for the Georgia Institute of Technology. The Georgia Tech Fiscal Year is July 1 through June 30.
**Rates are estimated for the period July 1, 1994 through June 30, 1995 and are subject to adjustment upon DCAA audit and ONR negotiations.

E. LIST OF CURRENT AND PENDING RESEARCH SUPPORT FOR PRINCIPAL INVESTIGATOR

(Paul G. Steffes)

A. Current Support

1. National Aeronautics and Space Administration - Grant NAGW-533, "Laboratory Evaluation and Application of Microwave Absorption Properties under Simulated Conditions for Planetary Atmospheres," $67,624 for 12-month period (11/1/93 - 10/31/94). P.I. time commitment: 25% (3 person-months). (THIS PROPOSAL IS FOR RENEWAL OF THIS GRANT.)

2. National Aeronautics and Space Administration, Lewis Research Center - Contract "RF Propagation Effects and ACTS Satellite Channel Characterization for Very Small Aperture Terminals," $48,187 (portion of overall contract covering this P.I.) for 16-month period (8/1/94-12/31/95). P.I. time commitment: 5% (0.8 person-months)

B. Pending Support (other than this proposal):

(None)

E. TABLE OF CONTENTS

I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or using laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. For example, laboratory measurements completed in this past year by DeBoer and Steffes (1994a) under Grant NAGW-533, have shown that the opacity from H_2S under simulated conditions for the outer planets is best described by a different lineshape than was previously used in theoretical predictions. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements <u>and</u> to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identify and abundance profiles of constituents in those planetary atmospheres.

II. OUTER PLANETS STUDIES

In this past grant year we have completed additional laboratory measurements of the microwave opacity and refractivity of gaseous H_2S under simulated conditions for the outer planets (i.e., in an H_2/He atmosphere at temperatures from 193 - 290 K, and at pressures from 2-6 Bars) using a new, computer-based measurement system. These measurements were made at 2.25 GHz (13.3 cm), 8.5 GHz (3.5 cm) and 21.7 GHz (1.4 cm), and showed opacity significantly greater than predicted by the Van Vleck-Weisskopf formalism. These results will appear in a paper by DeBoer and Steffes (1994a) in the June issue of <u>Icarus</u>. (Preprints were sent in January 1994.) We also include in this paper a revised formalism for computing opacity from H_2S under conditions for the outer planets, and apply that formalism to our radiative transfer model for Neptune. (We focus on Uranus and Neptune since they appear to be depleted of NH_3, and thus H_2S may significantly affect the emission from those planets.)

Of equal interest is the effect of H_2S on the microwave absorption in the atmosphere of Neptune measured by the Voyager 2 radio occultation experiment (Lindal, 1992). While Lindal (1992) originally concluded that H_2S could not be the source of the 3.6 and 13 cm opacities measured, our new laboratory results suggest that it could in fact account for this opacity, while still being consistent with the measured refractivity profiles. Inn the next grant year (November 1, 1994-October 31, 1995), we will attempt to apply the new results to original Voyage 2 radio occultation data, and to our own observations of Neptune's microwave emission. We will summarize our most recent work to date in this area at the 26th Annual Meeting of the Division for Planetary Sciences/American Astronomical Society to be held in Bethesda, Maryland on October 31, 1994-November 1, 1994. (Abstract attached as Appendix A, DeBoer and Steffes 1994b.) Likewise, we will present a description of our new, computer based microwave measurement system at the accompanying Sixth International Conference on Laboratory Research for Planetary Atmospheres on October 30 (DeBoer and Steffes, 1994c, see Appendix B).

III. VENUS STUDIES

A. Magellan Radio Occultation Experiments

In this past grant year (November 1, 1993 - October 31, 1994) we have continued to be active in using the Magellan spacecraft to probe the Venus atmosphere by way of radio occultation studies. Descriptions and results of the October 1991 experiments, which included three radio occultations probing down to the 33 km altitude level at approximately 60°N latitude and 110° solar zenith angle (early evening), will appear in the July issue of Icarus (Steffes et al., 1994 and Jenkins et al., 1994). (Reprints will be forwarded upon arrival.) Processing of data taken over Venus' southern hemisphere in December 1992 is currently being conducted by J. Jenkins (SETI Institute/NASA-Ames) under the VDAP program. We have also assisted in the planning and conduct of a final campaign of Magellan radio occultation experiments, which are currently being conducted by Jenkins and the Magellan Project staff. (We traveled to JPL on June 24 to conduct occultation experiments using DSN station DSS-14 at Goldstone, CA.)

One key aspect of the Magellan radio occultation results is the high percentage accuracy of the measured profiles of 13 cm and 3.6 cm absorptivity; typically ± 10-15%. This compares with uncertainties of ±80% for similar profiles from Pioneer-Venus occultation experiments (Jenkins and Steffes, 1991).

To take advantage of these new profiles, in order to develop highly accurate abundance profiles of the microwave absorbing constituents, one must know the microwave absorbing properties of the constituents very accurately. While carbon dioxide (CO_2) is a minor contributor to the microwave absorption at both wavelengths, its absorption properties are well understood (Ho et al., 1966) and since its abundance does not vary significantly, its effects can be directly subtracted. At 13 cm, the remaining opacity is almost all due to gaseous sulfuric acid (H_2SO_4). The best laboratory characterization of the 13 cm opacity from gaseous H_2SO_4 was conducted under this grant in 1984. (See Steffes, 1985) The measurements had accuracies of ±50% which far exceeded the accuracies of the opacity data at that time, and dramatically reduced the uncertainties (± factor-of-seven) of previous estimates of gaseous H_2SO_4 opacity. However, now that much better measurements of Venus atmospheric absorptivity have been made, better laboratory measurements are necessary.

These improved laboratory measurements are necessary not only at 13 cm, but also at 3.6 cm. Since at 13 cm, nearly all of the non-CO_2 opacity is due to gaseous H_2SO_4 abundance profiles can be obtained using only 13 cm measurements. However, the non-CO_2 absorptivity measured by the radio occultation experiments at 3.6 cm is due to both gaseous H_2SO_4 and SO_2. Thus, after an accurate abundance profile for gaseous H_2SO_4 is obtained from 13 cm data, then the effects of gaseous H_2SO_4 can be removed from the 3.6 cm absorptivity profile leaving only that absorption due to SO_2 (Jenkins et al., 1994). Thus, in order to obtain accurate SO_2 abundance profiles from the 3.6 cm absorptivity profiles, knowledge of the microwave absorption properties of gaseous H_2SO_4 at both 13 cm and 3.6 cm is required, in addition to very accurate knowledge of the microwave absorption properties of SO_2 at 3.6 cm.

B. Laboratory Measurements

Over the past grant year (November 1, 1993-October 31, 1994), we have initiated a program to more accurately characterize the microwave absorption properties of sulfur dioxide (SO_2) in a CO_2 atmosphere, especially with regard to its temperature dependence under simulated Venus conditions. Initially, we intended to focus on measurements around 22 GHz (approximately 1.38

cm), since our models and laboratory measurements have shown it to be one of the few wavelengths where gaseous H_2SO_4 opacity is relatively small, and SO_2 abundances could be deduced from emission measurements. However, the availability of highly accurate profiles of 3.6 cm opacity from the Magellan radio occultation experiments makes it possible to deduce SO_2 abundances at that wavelength, as well. Thus, we have increased the scope of the measurement program to include 1.38 cm, 3.6 cm, and 13.3 cm wavelengths over temperature and pressure ranges corresponding to the Venus atmosphere. These measurements are being conducted using the newly developed computer-based measurement system (DeBoer and Steffes, 1994c, see Appendix B). To date, measurements have been conducted at temperatures from 298K through 365K, and we hope to present results up to 500K at the upcoming Laboratory Measurements Conference. (Abstract attached as Appendix C, Suleiman and Steffes, 1994).

In the next grant year (November 1, 1994-October 31, 1995) we will conclude our work with SO_2 by completing the laboratory measurements and developing a highly accurate (within 10%) formalism for its opacity and refractivity, over the temperature ranges corresponding to the Venus atmosphere. Our formalism will be applied to both radio emission studies and radio occultation results to make more accurate estimates of SO_2 abundances. However, as mentioned previously, it is also necessary to have very accurate expressions for the absorption from gaseous H_2SO_4 at both 13 cm and 3.6 cm in order to accurately estimate SO_2 abundances from the Magellan 3.6 cm absorptivity profiles. Thus, we will also pursue design of a laboratory experiment measuring the absorption and refraction of gaseous H_2SO_4 at these two wavelengths, with accuracies comparable to that achieved the Magellan data. Part of this work has already begun with a more precise characterization of the vapor pressure behavior of sulfuric acid. (See Kolodner and Steffes, 1994, attached as Appendix D.)

IV. PROPOSED PROCEDURE AND LEVEL OF EFFECT

The proposed level of effort in the next grant year (November 1, 1994 through October 31, 1995) involves one professor (P.G. Steffes, Professor of Electrical and Computer Engineering) at 24% time, and one graduate student (Graduate Research Assistant David R. DeBoer) at 50% time, with supplies and other support as indicated in the attached cost breakdown (see page iv). (Note that 50% is the maximum support level for Ph.D. students with the remaining 50% considered as registered academic thesis research.) In addition to the participation in the program by Professor Steffes and the paid graduate research assistant, contributions to the program from both graduate and undergraduate students working on special projects for academic credit have been substantial. Two other Ph.D. students (Shady Suleiman, School of Electrical and Computer Engineering, and Marc Kolodner, School of Physics) are both conducting their Ph.D. research in the area of this grant with Georgia Tech support. Likewise, in the spirit of the NASA Graduate Student Researchers Program (Underrepresented Minority Focus), we continue to seek out talented underrepresented minority students and involve them in our program.

V. FACILITIES

The specific measurements described in this proposal will be conducted at the Radio Astronomy and Propagation Laboratory and the accompanying Remote Sensing Laboratory, which are located within the School of Electrical and Computer Engineering. A description of the equipment being used for these measurements has been given in the previous papers and reports. (e.g. DeBoer and Steffes, 1994a)

For support of any required data analysis and computing activities, a wide range of computing services for education, research, and administration is provided by the Georgia Tech Office of Information Technology. Numerous personal computers are also available to support this project.

VI. REFERENCES

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Steffes, P.G., J.M. Jenkins, R.S. Austin, S.W. Asmar, D.T. Lyons, E.H. Seale, and G.L. Tyler, 1994. Radio occultation studies of the Venus atmosphere with the Magellan spacecraft. 1. Experiment description and performance. Icarus 110, July 1994.

Suleiman, S.H. and P.G. Steffes, 1994. Laboratory measurement of the temperature dependence of gaseous sulfur dioxide (SO_2) microwave absorption under simulated conditions for the Venus atmosphere. To be presented at the Sixth International Conference on Laboratory Research for Planetary Atmospheres, Bethesda, MD, October 30, 1994. (See Appendix C.)

BIOGRAPHICAL SKETCH

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PROFESSOR
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332-0250

EDUCATION

S.B.	Electrical Engineering	1977
S.M.	Electrical Engineering Massachusetts Institute of Technology	1977
Ph.D.	Electrical Engineering Stanford University	1982

EMPLOYMENT HISTORY

Massachusetts Institute of Technology, Research Laboratory of Electronics, Radio Astronomy and Remote Sensing Group
Graduate Research Assistant — 1976-1977

Watkins-Johnson Company, Sensor Development, San Jose, California
Member of the Technical Staff — 1977-1982

Stanford University, Electronics Laboratory, Center for Radar Astronomy, Stanford, California
Graduate Research Assistant — 1979-1982

Georgia Institute of Technology, School of Electrical Engineering, Atlanta, Georgia
Assistant Professor — 1982-1988
Associate Professor — 1988-1994
Professor — 1994-Present

EXPERIENCE SUMMARY

At Massachusetts Institute of Technology

Responsible for development, operation, and data analysis for an 8-channel, 118 GHz radiometer system flown aboard the NASA Flying Laboratory (CV-990) as an engineering model for a meteorological sensing satellite. Duties included hardware development of millimeter-wave, microwave, analog, and A to D segments of the system, in addition to airborne operation and reduction of data. The research resulted in a Master's thesis entitled "Atmospheric Absorption at 118 GHz," detailing the first airborne measurement of high altitude atmospheric absorption in the 2.5 millimeter wavelength range, due to atmospheric oxygen.

At Watkins-Johnson Company

Responsibilities included proposals and system design and development, particularly in the area of millimeter-wave systems. Responsibility for millimeter-wave systems development included government sponsored study and development of ELINT (Electronic Intelligence) and radar warning receiving systems to frequencies as high as 110 GHz, as well as internal company sponsored development projects including a 60 GHz communications system and millimeter-wave downconverters.

At Stanford University

Research was concentrated in the area of microwave radio occultation experiments from Voyager and Mariner spacecraft, with specific interest in microwave absorption in planetary atmospheres. Work included computer-based theoretical development of microwave absorption coefficients for planetary atmospheres, to facilitate the use of radio occultation-derived microwave absorption profiles in determining constituent densities. Additional work included the development of a fully instrumented experimental facility for use in measuring the microwave properties of planetary atmospheres under simulated planetary conditions. The research resulted in a Ph.D. dissertation entitled "Abundances of Cloud-Related Gases in the Venus Atmosphere as Inferred from Observed Radio Opacity."

At Georgia Tech

Research Activities: Principal Investigator of the National Science Foundation Grant, "Remote Sensing of Clouds Bearing Acid Rain." This research studied and designed a microwave/millimeter-wave system for remotely sensing the pH of acidic clouds (1982-1983). Principal Investigator of the NASA Planetary Atmospheres Program, "Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres." This research includes study of the interaction between atmospheric constituents and electromagnetic waves, along with application of these studies to spacecraft and radio telescopic measurements of the microwave absorption in atmospheres of Venus and the outer planets (1984-1995). Principal Investigator of the GTE Spacenet Program, "Satellite Interference Locating System (SILS)." The program involved location of uplink signals on the surface of the earth without disrupting regular satellite operations (1986-1990). Principal Investigator of the Emory University/Georgia Tech Biomedical Technology Research Center, "Research in Development of a Non-Invasive Blood Glucose Monitoring Technique." This research involves the use of active infrared systems to determine glucose levels in the human eye and bloodstream (1988-1989), with subsequent support (1990-1991) from Lifescan, Inc. Principal Investigator of the NASA Pioneer Venus Guest Investigator Program, "Pioneer Venus Radio Occultation (ORO) Data Reduction: Profiles of 13 cm Absorptivity." This research infers 13 cm wavelength absorptivity profiles using the Pioneer Venus Orbiter, and then uses such profiles to characterize abundance profiles for gaseous H2SO4 in the Venus atmosphere (1988-1990). Principal Investigator/Team Member of NASA High Resolution Microwave Survey (HRMS). This research involves development and operation of the world's most sensitive receiving system used for a 1-10 GHz Sky Survey (1991-1994). Developer of atmospheric radio occultation experiments conducted with the Magellan (Venus) Spacecraft (1991-1994). Director of the Ku Band Satellite Earth Station System. Responsible for development of a Ku-band uplink/downlink system for use in inter-university networks (1985-1992).

Teaching Activities: Resource Professor for "Satellite Communications Systems" (graduate course) and "Electromagnetics III" (undergraduate required course covering waves, waveguides, and antennas). Have also taught "Electromagnetics II" (electrodynamics), "Signals and Systems," and "Survey of Remote Sensing."

HONORS AND AWARDS

Member, Eta Kappa Nu.
Member, Sigma Xi.
Senior Member, IEEE (Member of 6 IEEE Societies).
Recipient of the Stewart Award (MIT) for exceptional contribution to student extra-curricular life, 1977.
Recipient of the Metro Atlanta Young Engineer of the Year Award, presented by the Society of Professional Engineers, 1985.
Recipient of the Sigma Xi Young Faculty Research Award, 1988.
Associate Editor, *Journal for Geophysical Research* (JGR-Atmospheres), 1984-1989.
Appointed Member of the NASA Management and Operations Working Group for the Planetary Atmospheres Program (1986-1990).
Elected to The Electromagnetics Academy, October 1990.
Recipient of the Sigma Xi Best Faculty Paper Award, 1991.
Recipient of the NASA Group Achievement Award, "For outstanding contribution to the design, development, and operation of the High Resolution Microwave Survey Project, and its successful inauguraiton," March 1993.

OTHER PROFESSIONAL AFFILIATIONS

Member, American Association for the Advancement of Science.
Member, American Astronomical Society, Division for Planetary Sciences.
Member, American Geophysical Union.
Member, American Institute of Physics.
Member, American Society for Engineering Education.
Chairman, Atlanta Chapter, IEEE Antennas and Propagation Society and Microwave Theory and Techniques Society, 1986-1988.
Director, IEEE Atlanta Section, 1988-1989.
Georgia Tech Chapter, Sigma Xi, Vice President, 1990-1991; President, 1991-1992; Past-President, 1992-1993.
Chairman, Publicity Committee, 1993 IEEE International Microwave Symposium.

OTHER PROFESSIONAL ACTIVITIES

Proposal Reviewer for the NASA Planetary Astronomy Program, the NASA Planetary Atmospheres Program, the NASA Planetary Instrument Definition and Development Program, the NASA Voyager Data Analysis Programs, the NASA Exobiology Program, and the NSF Communications Research Program.
Reviewer/Referee for *Icarus* (International Journal of Solar System Studies), *Journal of Geophysical Research, Radioscience, IEEE Microwave and Guided Wave Letters*, and for several textbooks in the area of electromagnetics.
Consultant to industry in the areas of microwave, millimeter-wave, and RF systems for communications, detection, and monitoring. This includes satellite communications, antenna systems, and propagation.
Expert witness in cases involving antenna/communications system performance, and the effects of environmental factors on such systems.

PATENTS

E. H. Orr and P. G. Steffes, "Method and System for Detecting Water Depth and Piloting Vessels," Patent # 4,757,481, issued July 12, 1988.

R. V. Tarr and P. G. Steffes, "Non-Invasive Blood Glucose Measurement System," Patent #5,243,983, issued September 14, 1993.

PUBLICATIONS

Theses

P. G. Steffes, "A Microwave (UHF) Television Repeater System," S.B. Thesis, Massachusetts Institute of Technology, 1976.

P. G. Steffes, "Atmospheric Absorption at 118 GHz," S.M. Thesis, Massachusetts Institute of Technology, 1977.

P. G. Steffes, "Abundances of Cloud-Related Gases in the Venus Atmosphere as Inferred from Observed Radio Opacity," Ph.D. Dissertation, Stanford University, 1982.

Journal Publications

P. G. Steffes and R. A. Meck, "Prototype Tests Secure Millimeter Communications," *Microwave Systems News*, vol. 10, pp. 59-68, October 1980.

V. R. Eshleman, D. O. Muhleman, P. D. Nicholson, and P. G. Steffes, "Comment on Absorbing Regions in the Atmosphere of Venus as Measured by Radio Occultation," *Icarus*, vol. 44, pp. 793-803, December 1980.

P. G. Steffes and V. R. Eshleman, "Sulfur Dioxide and Other Cloud-Related Gases as the Source of the Microwave Opacity of the Middle Atmosphere of Venus," *Icarus*, vol. 46, pp. 127-131, April 1981.

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P. G. Steffes and V. R. Eshleman, "Sulfuric Acid Vapor and Other Cloud-Related Gases in the Venus Atmosphere: Abundances Inferred from Observed Radio Opacity," *Icarus*, vol. 51, pp. 322-333, August 1982.

P. G. Steffes, "Millimeter-Wavelength Remote Sensing of Stratospheric Sulfur Dioxide," *EOS*, vol. 64, pp. 198-199, May 1983.

P. G. Steffes, "Laboratory Measurements of the Microwave Opacity and Vapor Pressure of Sulfuric Acid Under Simulated Conditions for the Middle Atmosphere of Venus," *Icarus*, vol. 64, pp. 576-585, December 1985.

P. G. Steffes, "Evaluation of the Microwave Spectrum of Venus in the 1.2 to 22 cm Wavelength Range Based on Laboratory Measurements of Constituent Gas Opacities," *Astrophysical Journal*, vol. 310, pp. 482-489, November 1, 1986.

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J. M. Jenkins and P. G. Steffes, "Constraints on the Microwave Opacity of Gaseous Methane and Water Vapor in the Jovian Atmosphere," *Icarus*, vol. 76, December 1988.

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Presented at the *17th Annual Meeting of the Division of Planetary Sciences of the American Astronomical Society*, Baltimore, Maryland, October 1985.

P. G. Steffes, "Microwave Properties of the Atmospheres of the Outer Planets: Laboratory Measurements with the Georgia Tech Planetary Atmospheres Simulator," *Proceedings of the Laboratory Measurements for Planetary Science Workshop*, Meudon, France, pg. L-6, November 3, 1986.

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Presented at the *18th Annual Meeting of the Division of Planetary Sciences of the American Astronomical Society*, France, November 5, 1986.

P. G. Steffes, "Laboratory Measurements of the Millimeter-Wave Absorption from Gaseous Constituents Under Simulated Conditions for the Outer Planets," *Proceedings of the Laboratory Measurements for Planetary Science II Workshop*, Pasadena, California, pp. 6-7 through 6-8, November 9, 1987.

J. M. Jenkins and P. G. Steffes, "Limits of the Microwave Absorption of H_2O and CH_4 in the Jovian Atmosphere," *Bulletin of the American Astronomical Society*, vol. 19, pg. 695, 1987.

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J. Joiner, J. M. Jenkins, and P. G. Steffes, "Laboratory Measurements of the Opacity of Gaseous Ammonia (NH_3) in the 7.3-8.3 mm (36-41 GHz) Range Under Simulated Conditions for Jovian Atmospheres," *Bulletin of the American Astronomical Society*, vol. 19, pg. 694, 1987.

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P. G. Steffes, J. M. Jenkins, and M. J. Klein, "Observation of the Microwave Emission Spectrum of Venus from 1.3 to 3.6 cm," *Bulletin of the American Astronomical Society*, vol. 19, pg. 780, 1987.

Presented at the *19th Annual Meeting of the Division of Planetary Sciences of the American Astronomical Society*, Pasadena, California, November 11, 1987.

J. M. Jenkins and P. G. Steffes, "Preliminary Results for 13-cm Absorptivity Observed During Pioneer-Venus Radio Occultation Season #10 (1986-87)," *Bulletin of the American Astronomical Society*, vol. 20, pg. 834, 1988.

Presented at the *20th Annual Meeting of the Division of Planetary Sciences of the American Astronomical Society*, Austin, Texas, November 1, 1988.

J. Joiner, J. M. Jenkins, and P. G. Steffes, "Millimeter-Wave Measurements of the Opacity of Gaseous Ammonia (NH_3) Under Simulated Conditions for the Jovian Atmosphere," *Bulletin of the American Astronomical Society*, vol. 20, pg. 867, 1988.

Presented at the *20th Annual Meeting of the Division of Planetary Sciences of the American Astronomical Society*, Austin, Texas, November 3, 1988.

P. G. Steffes, "Laboratory Measurements of Microwave and Millimeter-Wave Properties of Planetary Atmospheric Constituents," *Laboratory Research for Planetary Atmospheres*, NASA Conference Publication CP-3077, pp. 5-26, 1990.

Presented at the *First International Conference for Laboratory Research for Planetary Atmospheres*, Bowie, Maryland, October 1989. (invited)

J. M. Jenkins and P. G. Steffes, "Potential Variability of the Abundance and Distribution of Gaseous Sulfuric Acid Vapor below the Main Cloud Deck in the Venus Atmosphere," *Bulletin of the American Astronomical Society*, vol. 21, pg. 925, 1989.

Presented at the *21st Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society*, Providence, Rhode Island, October 31, 1989.

P. G. Steffes, "Evidence for Temporal Variations in SO_2 Abundance in the Sub-Cloud Region of the Venus Atmosphere," *Bulletin of the American Astronomical Society*, vol. 21, pg. 925, 1989.

Presented at the *21st Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society*, Providence, Rhode Island, October 31, 1989.

A. K. Fahd and P. G. Steffes, "Laboratory Measurements of the Dissociation Factor of Gaseous Sulfuric Acid (H_2SO_4)," *Bulletin of the American Astronomical Society*, vol. 21, pg. 927, 1989.

Presented at the *21st Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society*, Providence, Rhode Island, November 1, 1989.

J. Joiner and P. G. Steffes, "Models of the Millimeter-Wave Emission of the Jovian Atmosphere Utilizing Laboratory Measurements of Gaseous Ammonia (NH_3)," *Bulletin of the American Astronomical Society*, vol. 21, pg. 945, 1989.

Presented at the *21st Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society*, Providence, Rhode Island, November 1, 1989.

W. W. Smith and P. G. Steffes, "A Satellite Interference Location System using Differential Time and Phase Measurement Techniques," *Proceedings of the IEEE International Carnahan Conference on Security Technology: Crime Countermeasures*, publ. no. 90CH2892-8, pps. 38-41, 1990.

Presented at the *IEEE International Carnahan Conference on Security Technology: Crime Countermeasures*, Lexington, Kentucky, October 11, 1990.

A. K. Fahd and P. G. Steffes, "Laboratory Measurements of the 1.3 and 13.3 cm Opacity of Gaseous SO_2 under Simulated Conditions of the Middle Atmosphere of Venus," *Bulletin of the American Astronomical Society*, vol. 22, pg. 1032, 1990.

Presented at the *22nd Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society*, Charlottesville, Virginia, October 22, 1990.

A. K. Fahd and P. G. Steffes, "Laboratory Measurement of the Millimeter-Wave Properties of Liquid Sulfuric Acid (H_2SO_4) Between 90 and 100 GHz," *Bulletin of the American Astronomical Society*, vol. 22, pg. 1035, 1990.

Presented at the *22nd Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society*, Charlottesville, Virginia, October 22, 1990.

J. Joiner and P. G. Steffes, "Study of Millimeter-Wave Absorbing Constituents in the Jovian Atmospheres," *Bulletin of the American Astronomical Society*, vol. 22, pg. 1032, 1990.

> Presented at the *22nd Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society*, Charlottesville, Virginia, October 22, 1990.

J. M. Jenkins and P. G. Steffes, "Sulfuric Acid Vapor Profiles for the Atmosphere of Venus Below the Main Cloud Deck," *Bulletin of the American Astronomical Society*, vol. 22, pg. 1055, 1990.

> Presented at the *22nd Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society*, Charlottesville, Virginia, October 23, 1990.

P. G. Steffes and J. M. Jenkins, "Atmospheric Radio Occultation Measurements with Magellan at Venus," *JPL Publication*, JPL-D-8581, pp. B1-B8, 1991.

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A. K. Fahd and P. G. Steffes, "Laboratory Measurements of the Millimeter-Wave (3 mm) Opacity of Gaseous SO_2 under Simulated Conditions of the Middle Atmosphere of Venus," *Bulletin of the American Astronomical Society*, vol. 23, p. 1194, November 1991.

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JUNE 1994

DIVISION FOR PLANETARY SCIENCES ABSTRACT FORM

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Radiative Transfer Results for Neptune Microwave Emission [1]

D. R. DeBoer, P. G. Steffes (Georgia Institute of Technology)

Recently it has been shown that the microwave opacity of H_2S is greater than previously modeled and that it could possibly be responsible for the microwave opacity in Neptune's troposphere measured by Voyager 2 radio occultation (DeBoer and Steffes Icarus 109, June 1994). This paper examines that proposal in greater detail by comparing results from a radiative transfer model with radio telescope and Voyager radio occultation observations.

Sub-solar quantities of NH_3 ($\leq$ 5 ppm) are needed below the putative NH_4SH cloud near 35 bars to match the relatively high brightness temperature near 1 GHz measured by the VLA (de Pater and Richmond, Icarus 80,1-13, 1989). This value (5 ppm) also reproduces the sharp dip in emission measured above 1 GHz but requires that essentially no H_2S be present throughout the entire atmosphere. Other abundance profiles which seem to better describe the measured spectrum between 100-200 GHz include relatively large H_2S abundances along with NH_3 depletions. These suffer at frequencies with weighting functions peaking near the NH_4SH cloud (roughly 5-10 GHz). The microwave extinction due to NH_4SH is currently poorly known and could possibly play a role at these frequencies. Both profiles yield absorptivities which are similar to those measured by Voyager 2 near 6 bars.

[1] This work was supported by the NASA Planetary Atmospheres Program under grant NAGW-533.

ORAL PAPER [X] POSTER PAPER [ ] EITHER [ ]

PAPER MUST BE PRESENTED BY FIRST AUTHOR

Would you be willing to act as Session Chair? Yes [X] No [ ]

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Signature of Introducing Member, if Author is a Nonmember

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Is your abstract especially newsworthy, and if so, would you be willing to prepare a news release and be available for interviews with reporters?

Yes [ ] No [X] Maybe [ ]

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Abstracts must conform to the AAS style as described on the back of this form. **Abstract original MUST be typed or glued directly onto this form.** The charge for publication of this abstract in the Bulletin of the American Astronomical Society will be included in the registration fee for this meeting.

Deadline for receipt of abstract: **July 1, 1994**

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APPENDIX A

Abstract Submitted for the Division for Planetary Sciences D.C. Meeting

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APPENDIX B: To be presented at the Sixth International Conference on Laboratory Research for Planetary Atmospheres, October 30, 1994.

The Georgia Tech High Sensitivity Microwave Measurement System [1]

David R. DeBoer and Paul G. Steffes
Georgia Institute of Technology
School of Electrical and Computer Engineering
Atlanta, GA 30332-0250

As observations and models of the planets become increasingly more accurate and sophisticated, the need for highly accurate laboratory measurements of the microwave properties of the component gases present in their atmospheres become ever more critical. This paper describes the system that has been developed at Georgia Tech to make these measurements. Descriptions of previous versions of this system have been published (e.g. DeBoer and Steffes, Icarus **109**, June 1994) and here we will discuss newly added features as well as some ideas for future improvement.

The Georgia Tech system uses changes in the quality factor and center frequency of a resonator with the test gas present to measure absorptivity and refractivity. These changes are monitored using a swept signal source and a spectrum analyzer. The largest single improvement to the system has been automation of this monitoring using a personal computer that allows remote control of the spectrum analyzer as well as access to the spectrum analyzer data. Once the data has been read into the computer one can apply appropriate digital signal processing techniques to reduce the data to a more useful form. This standardizes the determination of the parameters of the cavity resonance and greatly increases the reliability of the system.

Furthermore, the attenuator previously used between the sweeper and the resonator to provide isolation has been replaced by an isolator. This provides a 10 dB increase in the signal to noise ratio (SNR) as well as 20 dB of extra isolation. This extra isolation allows the sweepers to be operated at a higher power setting to further increase the SNR. Possible future improvements include coating the inside of the pressure vessel containing the resonator with absorbing material to reduce coupling between the pressure vessel and the resonator as well as inclusion of a master-slave interface between the sweeper and spectrum analyzer.

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[1]This work was supported by the NASA Planetary Atmospheres Program under grant NAGW-533.

APPENDIX C: To be presented at the Sixth International Conference on Laboratory Research for Planetary Atmospheres, October 30, 1994.

Laboratory Measurement of the Temperature Dependence of Gaseous Sulfur Dioxide (SO_2) Microwave Absorption Under Simulated Conditions for the Venus Atmosphere [1]

Shady H. Suleiman and Paul G. Steffes
Georgia Institute of Technology
School of Electrical and Computer Engineering
Atlanta, GA 30332-0250

It is well known that gaseous sulfur dioxide (SO_2) is one of the major absorbers in the Venus atmosphere at microwave and millimeter-wave frequencies. In their paper, Fahd and Steffes (Icarus 97, 200-210, 1992) have shown results of laboratory measurements of the microwave and millimeter wave opacity of gaseous SO_2 in a CO_2 atmosphere which were used to infer an abundance profile for gaseous SO_2 in the atmosphere of Venus. However, no measurement of the temperature dependence of the gaseous SO_2 opacity were made. As a result, laboratory measurements of the opacity of gaseous SO_2 at characteristic temperatures of the Venus atmosphere are of great importance. These measurements will result in a more accurate abundance profile of gaseous SO_2 in the Venus atmosphere. Accordingly, laboratory measurements of the temperature dependence of the opacity from gaseous SO_2 in a CO_2 atmosphere at temperatures from 290 K to 500 K and at pressures from 1 to 4 atmospheres are currently being conducted at 2.25 GHz (13.3 cm), 8.5 GHz (3.5 cm) and 21.7 GHz (1.4 cm). The gaseous mixture consists approximately of 8.3% SO_2, and 91.7% CO_2. The results will then be used to develop a model to characterize the opacity of gaseous SO_2 in the Venus atmosphere.

[1] This work was supported by the NASA Planetary Atmospheres Program under grant NAGW-533.

APPENDIX D: To be presented at the Sixth International Conference on Laboratory Research for Planetary Atmospheres, October 30, 1994.

On the Saturation Vapor Pressure and Millimeter-Wave Opacity of Gaseous Sulfuric Acid (H_2SO_4) Under Venus-Like Conditions

Marc A. Kolodner
School of Physics
Georgia Institute of Technology
Atlanta, GA 30332-0430

Paul G. Steffes
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0250

Laboratory measurements of the saturation vapor pressure of sulfuric acid were presented by Fahd and Steffes (*B.A.A.S.*, 21, p. 927, 1989) in the 500-600 K temperature region. This data, though, is not consistent with either results from Ayers et al. (*Geophys. Res. Let.*,7, p. 433, 1980) giving partial pressures in the lower temperature regime or with the partial pressure at the boiling point calculated by Vermeulen et al. (in *Perry's Chem. Eng. Handbk.*, 6th ed., p. 3-68, 1984). We have attempted to correct errors which have been found both in the experimental setup and the principle theory. First, the junction of the thermocouple used in the experiment was not referenced to a known cold temperature. We believe that the thermocouple reference junction temperature was 20°C at the coolest temperature and rose to 70°C at the highest temperature, and we have adjusted the original data accordingly. A second error was due to an assumption made that the concentration of H_2SO_4 was the same in the vapor phase as it was in the liquid phase (98.7%). At these high temperatures of operation though, much of the free water will have evaporated and the concentration of H_2SO_4 in the vapor phase will be less than 98.7%. As an upper limit, we assume that all of the free water was vaporized. The corrected data is now consistent with the Clausius-Clapeyron model of Ayers et al. Their model, though, is not consistent with the partial pressure of H_2SO_4 at the boiling point. Thus, we have developed a model similar to Ayers et al. except that the effect of the temperature dependence of the latent heat of vaporization has been included. The importance of this effect was first realized by Kulmala and Laaksonen (*J. Chem. Phys.*, 93, p. 696, 1990).

This model, which is consistent with all data points of the saturation vapor pressure of H_2SO_4, can be used to recalibrate earlier laboratory measurements of millimeter-wave opacity (normalized to mixing ratio) of gaseous H_2SO_4 in a CO_2 environment presented by Fahd and Steffes (Int. Conf. on Lab. Res. for Planet. Atmos., SP-20, 1991). Finally, we have produced a Van Vleck-Weisskopf model of millimeter-wave opacity which is consistent with the corrected data at pressures of 1 and 2 atmospheres using a CO_2-H_2SO_4 line broadening parameter of 16 MHz/torr.

This work was supported by the NASA Planetary Atmospheres program under Grant NAGW-533.

APPENDIX E

Supplemental Proposal for Education Research Activities:

Title: Radioscientific Studies of Planets

Principal Investigator: Professor Paul G. Steffes
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0250
(404) 894-3128
email: ps11@prism.gatech.edu

Graduate Student Applicant: Mr. Scott A. Borgsmiller
(will begin Ph.D. studies in September 1994)

A. SUMMARY

As part of a program to involve students in a "hands-on" experience in space science and engineering, a student-run radio observatory has been developed by Georgia Tech in Woodbury, GA, approximately 65 miles from the Atlanta campus. The Woodbury Research Facility is a student-run radio observatory which was converted from use as a satellite uplink site. (See Attachment #1) The observatory consists of two 30-meter diameter parabolic dish antennas, one of which has been converted for use as a radio telescope. We will have the full use of the facility for as much time as we deem necessary to conduct experiment and observations. The proximity to campus makes it possible to involve large numbers of students in the observational projects and student teams have already been formed to support such activities, with over 50 undergraduates and graduate students (largely volunteer) being involved. Similarly, the proximity to Atlanta and the Georgia Tech campus will make it possible to involve groups of high school mathematics and science teachers attending summer institutes offered on campus.

We have already begun a demonstration program to monitor changes in the 5 cm-wavelength continuum emission from the Jovian atmosphere before, during, and after the collision of Comet Shoemaker - Levy 9 (See Attachment #2, Steffes, et al., 1994, to be presented at the DPS/AAS Meeting, November 1994, Bethesda, MD.) This program involves a large number of graduate and undergraduate volunteers, as well as a more senior Ph.D. student (David R. DeBoer) who is using laboratory measurements and radiative transfer models developed under our Planetary Atmospheres grant to predict possible effects of the comet collision, and will assist in interpreting observational data. However, since David DeBoer will graduate in 1995, and another advanced Ph.D. student will be supported to work on additional laboratory measurements, support for a new Ph.D. student is being sought under this supplemental proposal.

The student to be supported is Mr. Scott A. Borgsmiller. Mr. Borgsmiller completed his B.S.E.E. degree in 1989 at the University of Illinois, and he completed the M.S.E.E. degree at Syracuse University while working for the Martin Marietta Company - Ocean, Radar, and Sensor Systems Division. He will begin his Ph.D. studies in September 1994. His work in experimental and observational radioscience will complement both our work on laboratory measurements of the microwave properties of simulated planetary atmospheres, and our work on modelling the propagation and radiative transfer effects in planetary atmospheres. We hope that accurate measurements of the continuum emission from Neptune might be made over a period of time so as to resolve the possible presence of H_2S (DeBoer and Steffes, Icarus 109, July 1994). Also, one undergraduate who has distinguished himself or herself in work at the facility will receive support to assist in this work.

One of the key aspects of this program is its ability to provide an educational experience for large numbers of graduate and undergraduate student,s as well as for a substantial number of primary and secondary school science and mathematics teachers.

As mentioned previously, a team of over 50 graduate and undergraduate students has currently been formed to complete work on the radio telescope and to conduct experiments. Likewise, because of the proximity to Atlanta, 60 high school mathematics and science teachers who are involved with the Georgia Industry Fellowships for Teachers (GIFT) Program would be directly involved with observations or experiments. (Note that GIFT is a program which provides summer opportunities for science and mathematics teachers to become involved first-hand in research and is funded through the Georgia Statewide Systematic Initiative of the NSF.)

In addition, it is expected that primary and secondary math and science teachers from economically disadvantaged areas in the state would be supported to be present through the Atlanta Project, a non-profit urban development organization. Support will also be solicited from the Eisenhower Fellowship Program to offer a one- or two-week experience for such teachers.

Statement of Interest:

This is to express my interest in the NASA Deep Space Research Program. I will be attending the Georgia Institute of Technology starting in the Fall of 1994. I will be working towards a doctorate in electrical engineering. I am interested in doing research work in the study of electromagnetics in space applications. I would like to do research work in deep-space (beyond Earth orbit) communications and remote sensing. This includes communication with interplanetary space probes and the remote sensing of other planets using probes or ground based radio telescopes. I have always been interested in astronomy and space exploration, and I am excited about the opportunity to combine this with my interest in electromagnetics. The Galileo and Cassini missions should provide many opportunities for remote sensing studies of planetary atmospheres in the next decade.

The facilities at Georgia Tech to perform this type of research are extensive. The School of Electical Engineering has many laboratories devoted to work in this area. These include the Radio Astronomy and Propagation Laboratory, the Remote Sensing Laboratory, and the Satellite Earth Station Facility. In addition, the Institute has recently acquired 30m dish system located just outside of Atlanta. This facility is ideal for performing deep space measurements. A great deal of research has already been performed in this field by Professor Paul Steffes and his graduate students. This is one of my primary reasons for selecting Georgia Tech for graduate study.

Scott Borgsmiller
June 20, 1994

POTENTIAL TOPICS:

1. Observations of microwave emission from the outer planets at wavelengths suggested by laboratory measurements and radiative transfer modelling.
2. Venus observations at 2.2 cm.
3. Coordinated observations with Galileo entry probe absorptivity measurements.

C. Educational Program

One of the key aspects of this program is its ability to provide an educational experience for large numbers of graduate and undergraduate students, as well as for a substantial number of primary and secondary school science and mathematics teachers.

As mentioned previously, a team of over 50 graduate and undergraduate students has currently been formed to complete work on the radio telescope and to conduct experiments. Likewise, because of the proximity to Atlanta, 60 high school mathematics and science teachers who are involved with the Georgia Industry Fellowships for Teachers (GIFT) Program would be directly involved with observations or experiments. (Note that GIFT is a program which provides summer opportunities for science and mathematics teachers to become involved first-hand in research and is funded through the Georgia Statewide Systematic Initiative of the NSF.)

In addition, it is expected that primary and secondary math and science teachers from economically disadvantaged areas in the state would be supported to be present through the Atlanta Project, a non-profit urban development organization. Support will also be solicited from the Eisenhower Fellowship Program to offer a one- or two-week experience for such teachers.

The basic program to be offered to teachers will include a one week summer workshop in which the teachers will be introduced to study of the solar system, and will conclude the weeklong program by actually experiencing an observation or experiment at the Woodbury Research facility. Some teachers supported by the GIFT Program will actually be involved directly with the Georgia Tech graduate and undergraduate students for the full ten-week long summer program, and will directly be involved with planning or conduct of experiments or observations.

The summer program would be taught by the Principal Investigator (P.G. Steffes), with assistance from students involved with the program. As mentioned previously, support for the teachers attending the programs will be obtained from other sources.

STATUS REPORT #20
AND RENEWAL PROPOSAL ENTITLED

LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

to the

National Aeronautics and Space Administration
for Grant NAGW-533

(A Supplemental Proposal for Educational Research Activities is attached as Appendix E.)

Report Period:	November 1, 1993 through October 31, 1994
Proposed Renewal Period:	November 1, 1994 through October 31, 1995

D. BUDGET SUMMARY

Supplement to Grant NAGW-533 for Educational Research Activities

For the Period of November 1, 1994 through October 31, 1995

ESTIMATED COST BREAKDOWN

I.	DIRECT SALARIES AND WAGES*			$22,111
	A.	Principal Investigator P.G. Steffes 4% time, calendar year (.04 person-years)	$ 3,196	
	B.	1 Graduate Student (S.A. Borgsmiller) 50% time, calendar year (.5 person-years)	$15,000	
	C.	1 Undergraduate Assistant 25% time, calendar year (.25 person-years)	$ 3,915	
II.	FRINGE BENEFITS** 24.1 % of Direct Salaries & Wages (less students)			$ 789
III.	MATERIALS, SUPPLIES AND SERVICES (Supplies for Experiments)			$ 800
IV.	TRAVEL			$ 1,300
	A.	Travel for Student to AAS/DPS Meeting (Hilo, HI, 6 days duration, airfare $600 plus registration and $100/day)	$ 1,300	
		SUBTOTAL-ESTIMATE OF DIRECT COSTS		$25,000
V.	OVERHEAD (Indirect Expense)** 40% of Modified Total Direct Cost Base			$10,000

TOTAL BUDGET (12 months) REQUESTED FROM NASA: $35,000

ESTIMATED TOTALS TO COMPLETION OF RESEARCH:
Funds: $140,000 Months: 48

*The salary and wage rates are based on FY 95 salaries for the Georgia Institute of Technology. The Georgia Tech Fiscal Year is July 1 through June 30.
**Rates are estimated for the period July 1, 1994 through June 30, 1995 and are subject to adjustment upon DCAA audit and ONR negotiations.

Attachment #1
(Appendix E)

Woodbury Facility offers valuable research jobs

By Allen Turner
Campus Life Staff

Would you like to receive engineering credit while obtaining real work experience? This opportunity is now available in the School of Electrical Engineering under the direction of Research Engineer, Dr. Whit Smith. The Georgia Tech Woodbury Research Facility is located in Meriwether County, some seventy miles southeast of Atlanta. This former AT&T satellite uplink facility is being converted to a laboratory for radio astronomy.

The Woodbury facility was built in the mid 1970's as one of a series of earth stations for AT&T's satellite telephone network. The technology of that day limited satellite output powers in the 4-6 gHz C-Band to about fifteen Watts. Elaborate methods were used to receive as much signal from the satellite as possible.

The site is surrounded by a ring of hills, which effectively shield it from the terrestrial microwave noise of Atlanta. The dishes are thirty meters in diameter, and the low noise amplifiers employed cryogenic cooling on the first stage. As technology rapidly improved in the early 1980's, wideband satellite communication became possible with dishes located in and around Atlanta, and the Woodbury site became obsolete. AT&T mothballed the site in the early 1980's, removing the microwave apparatus and much of the equipment necessary for dish motion.

The Georgia Tech Research Corporation acquired the site in 1993. Shortly thereafter, it was decided that the site would be converted for use in radio testing and research. The same factors that made Woodbury ideal for early satellite communications make it ideal for radio astronomy. In taking the student work approach, completion will take longer, but a substantial cost savings will be realized. More importantly, students now have the chance to work on

See WOODBURY, page 20

Woodbury from page 17

the ground floor of an exciting project for credit.

Currently, about thirty undergraduate and graduate students are involved. During the year that work has been ongoing, about fifty students have worked on the project in several key areas.

The primary goals of the past year have been to restore azimuth and elevation motion to both dishes, develop computer software control of the dishes, and design and optimize RF equipment for the site.

Georgia Tech students may register to work on the project in one of two ways. Credit may be obtained as part of a three-course series of UROP (Undergraduate Research Opportunities) or as a one quarter special topics course.

The project is not restricted by majors, as Dr. Smith is looking for assistance from both Electrical and Mechanical Engineering students. If you have an interest in learning more about the Woodbury project, contact Dr. Whit Smith in the School of Electrical Engineering at 894-3185, or through e-mail at whit.smith@ee.gatech.edu.

Georgia Tech

Research News

Georgia Institute of Technology
Research Communications Office
Atlanta, Georgia 30332-0800
USA
404-894-3444

For Immediate Release
July 5, 1994

SAVED BY STUDENT ENGINEERS, 105-FOOT DISH PROVIDES NEW CAPABILITIES TO STUDY COMMUNICATIONS & RADIO ASTRONOMY

When pieces of the Shoemaker-Levy Comet begin crashing into Jupiter on July 16, researchers from the Georgia Insitute of Technology expect to be listening in with a 105-foot radio telescope rescued from years of disuse by teams of student engineers.

The scientists hope that changes in the microwave energy emitted by Jupiter will provide clues to the physical results of the comet impacts. They plan to analyze microwave emissions at wavelengths of five centimeters, potentially adding to information that will be gathered by radio astronomers worldwide. (See related article.)

Georgia Tech researchers make final adjustments near the feed room of an antenna at its Woodbury Research Facility. (Color/B&W Available)

The 105-foot dish is one of a pair of 10-story antennas built in the 1970s as part of a former AT&T satellite tracking facility located in Woodbury, about 65 miles southwest of Atlanta. Routine satellite communication no longer requires such large dishes, but their size makes them ideal for such tasks as gathering data from deep space, measuring weak electromagnetic phenomena that affect satellite communications -- and even assessing the man-made noise hampering radio astronomy.

"When you are trying to observe things that are much farther away than satellites, or if you are trying to measure very weak effects due to phenomena that aren't communications related, you need large antennas," said Dr. Paul Steffes, a professor in Georgia Tech's School of Electrical and Computer Engineering. "These dishes

- OVER -

FOR MORE INFORMATION:

ASSISTANCE/PHOTO: John Toon (404-894-6986), Jackie Nemeth (404-894-2906) or Lea McLees (404-853-9079); Internet: john.toon@gtri.gatech.edu; CompuServe: 71045,164
TECHNICAL: Dr. Paul Steffes, (404-894-3128) or Dr. William "Whit" Smith, (404-894-3185)
WRITER: John Toon

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Observations of the Jovian Microwave (5cm) Emission During and Subsequent to the Collision with Comet Shoemaker - Levy 9

P.G. Steffes, D.R. DeBoer, W.W. Smith (Georgia Institute of Technology)

A student-faculty observational project has been undertaken whereby the 5 cm continuum emission from Jupiter is being monitored both before and after the collision of Comet Shoemaker - Levy 9. Disk-averaged flux density variations of 0.5% are detectable with the system developed, which uses a 30-meter radio telescope at the Georgia Tech Woodbury Research Facility, 65 miles south of Atlanta. This facility has been developed by a team including over 50 students.

The 5 cm flux from Jupiter is largely thermal (75%) and will be subject to variations depending on the depth of the comet's penetration, a well as the redistribution and spreading of microwave absorbers carried up from the deeper atmosphere by the vertical shock waves. The non-thermal, synchrotron emission at 5 cm (approximately 25%), could likewise be affected by the injection of either cometary material or Jovian atmospheric constituents into the magnetosphere.

Aswith any continuum measurement, large bandwidths (>500 MHz) are desirable so as to increase sensitivity. However, spectral crowding in the centimeter wavelength range has made it more difficult to obtain interference-free observing spectrum, especially given the large number of spaceborne transmitters. New approaches for addressing this problem are presented.

This work was supported by the NASA Planetary Atmospheres Program under Grant NAGW-533.

Abstract Submitted for the Division for Planetary Sciences D.C. Meeting

Date Submitted ____________ Form Version 4/94

ORAL PAPER ☐ POSTER PAPER ☒ EITHER ☐

PAPER MUST BE PRESENTED BY FIRST AUTHOR

Would you be willing to act as Session Chair? Yes ☒ No ☐

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Membership Status (First Author):

DPS-AAS Member ☒ Non-Member ☐

Student Member ☐ Student Non-Member ☐

Is your abstract especially newsworthy, and if so, would you be willing to prepare a news release and be available for interviews with reporters?

Yes ☒ No ☐ Maybe ☐

DPS Category No. 21 (from list on separate page)

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Deadline for receipt of abstract: **July 1, 1994**

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Georgia Tech

Research News

Georgia Institute of Technology
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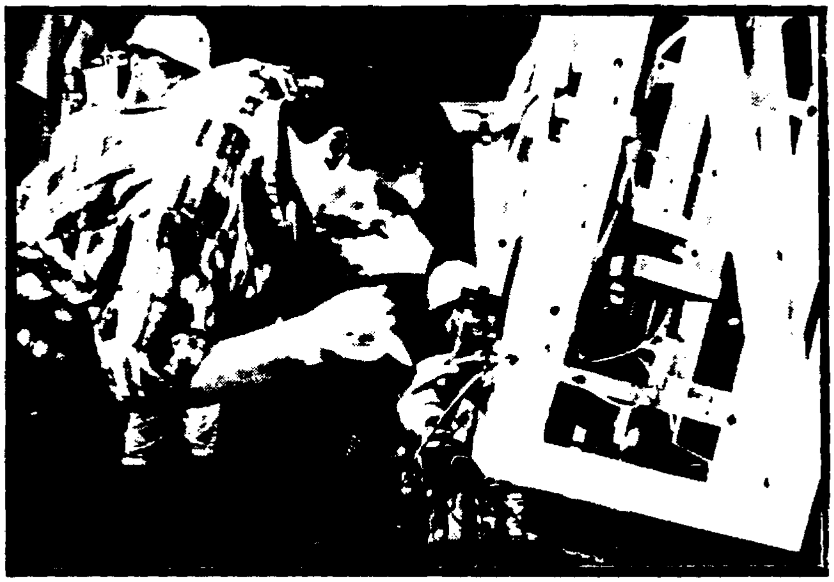
For Immediate Release
July 5, 1994

RADIO ASTRONOMERS TO MEASURE EFFECTS OF SHOEMAKER-LEVY COMET COLLISION ON JUPITER'S ATMOSPHERE AND TEMPERATURE

As the attention of the international scientific community turns to the Shoemaker-Levy Comet's collision course with the planet Jupiter, researchers at the Georgia Institute of Technology will measure the microwave noise that the solar system's largest planet will radiate before, during, and after the 21 comet fragments strike.

By taking radiation intensity measurements at a satellite tracking facility located in Woodbury, Georgia, the researchers hope to find out more about Jupiter's physical temperature and gases. The radiation intensity is related to the physical temperature of the planet and its atmospheric constituents, according to Dr. Paul G. Steffes, a professor in Georgia Tech's School of Electrical and Computer Engineering. (See related story on Woodbury facility.)



Research Engineer William "Whit" Smith helps radio astronomy group install equipment for monitoring Jupiter's microwave emissions. (Color/B&W Available).

"When we measure radiation intensity, we can make inferences on temperature and the abundance of certain kinds of gases in the atmosphere," says Steffes. "We can also infer something about where in the atmosphere those gases lie."

The Georgia Tech researchers have modeled several scenarios for how the comet may affect microwave emissions from the planet. Steffes and his Ph.D. student, David DeBoer, believe that the Shoemaker-Levy Comet could produce new gases and that it could take the gases that are deeply embedded in Jupiter's atmosphere and raise them to a higher level where their effects will be more observable.

FOR MORE INFORMATION:

ASSISTANCE/PHOTO: Jackie Nemeth (404-894-2906); John Toon (404-894-6986) or Lea McLees (404-853-9079); CompuServe: 71045,164; Internet: jackie.nemeth@ee.gatech.edu or john.toon@gtri.gatech.edu. TECHNICAL: Please see contact list at end of release. WRITER: Jackie Nemeth

- OVER -

(Enclosure 1)

Proposal No.: 02.105.002.95.002

Principal Investigator: Dr. Paul G. Steffes

Title: Laboratory Evaluation and Application of Microwave Absorption Properties under Simulated Conditions for Planetary Atmospheres

Certification Regarding Debarment, Suspension, and Other Responsibility Matters--Primary Covered Transactions

(1) The prospective primary participant certifies to the best of its knowledge and belief, that it and its principals:

(a) Are not presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department of agency;

(b) Have not within a three-year period preceding this proposal been convicted of or had a civil judgment rendered against them for commission of fraud or a criminal offense in connection with obtaining, attempting to obtain, or performing a public (Federal, State or local) transaction or contract under a public transaction; violation of Federal or State antitrust statutes or commission of embezzlement, theft, forgery, bribery, falsification or destruction of records, making false statements, or receiving stolen property;

(c) Are not presently indicted for or otherwise criminally or civilly charged by a governmental entity (Federal, State or local) with commission of any of the offenses enumerated in paragraph (1)(b) of this certification; and

(d) Have not within a three-year period preceding this application/proposal had one or more public transactions (Federal, State or local) terminated for cause or default.

(2) Where the prospective primary participant is unable to certify to any of the statements in this certification, such prospective participant shall attach an explanation to this proposal.

Certified By:

7/12/94

(Signature) (Date)

Janis L. Goddard

(Typed Name)

Contracting Officer

(Title)

Georgia Tech Research Corporation

(Institution)

(Enclosure 1)

CERTIFICATION REGARDING LOBBYING

Certification for Contracts, Grants, Loans, and Cooperative Agreements.

The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No Federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned. to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any Federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooeprative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, "Disclosure Form to Report Lobbying," in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers (including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements) and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000, and not more than $100,000 for each such failure.

Certified by:

Authorized Official (Signature) 7/12/94
Date

Janis L. Goddard
Typed Name

Contracting Officer
Title

Georgia Tech Research Corporation
Institution

(Enclosure 1)

Certification Regarding Drug-Free Requirements

A. The grantee certifies that it will provide a drug-free workplace by:

(a) Publishing a statement notifying employees that the unlawful manufacture, distribution, dispensing, possession or use of a controlled substance is prohibited in the grantee's workplace and specifying the actions that will be taken against employees for violation of such prohibition;

(b) Establishing a drug-free awareness program to inform employees about --

(1) The dangers of drug abuse in the work place;

(2) The grantee's policy of maintaining a drug-free workplace

(3) Any available drug counseling, rehabilitation, and employee assistance programs; and

(4) The penalties that may be imposed upon employees for drug abuse violations occurring in the workplace;

(c) Making it a requirement that each employee to be engaged in the performance of the grant be given a copy of the statement required by paragraph (a);

(d) Notifying the employee in the statement required by paragraph (a) that, as a condition of employment under the grant, the employee will --

(1) Abide by the terms of the statement and

(2) Notify the employer of any criminal drug statute conviction for a violation occurring in the workplace no later than five days after such conviction.

(e) Notifying the agency within ten days after receiving notice under subparagraph (d)(2) from an employee or otherwise receiving actual notice under subparagraph (d)(2), with respect to any employee who is so convicted--

(f) Taking one of the following actions within 30 days of receiving notice under subparagraph (d)(2), with respect to any employee who is so convicted--

(1) Taking appropriate personnel action against such an employee, up to and including termination; or

(2) Requiring such employee to participate satisfactorily in a drug abuse assistance or rehabilitation program approved for such purposes by a Federal, State, or local health, law enforcement, or other appropriate agency;

(g) Making a good faith effort to continue to maintain a drug-free workplace through implementation of paragraphs (a), (b), (c), (d), (e) and (f).

B. The grantee shall insert in the space provided below the site(s) for the performance of work done in connection with the specific grant:

Place of Performance (Street address, city, county, state, zip code)

Georgia Institute of Technology, Atlanta, Fulton County, Georgia 30332

Certified By:

7/12/94

(Signature) (Date)

Janis L. Goddard

(Typed Name)

Contracting Officer

(Title)

Georgia Tech Research Corporation

(Institution)

E-21-643
21

FULL RENEWAL PROPOSAL
AND
STATUS REPORT #21

ENTITLED

LABORATORY EVALUATION AND APPLICATION OF
MICROWAVE ABSORPTION PROPERTIES UNDER
SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

to the

National Aeronautics and Space Administration
for Grant NAGW-533

Report Period:	November 1, 1994 through October 31, 1995
Proposed Renewal Period:	November 1, 1995 through October 31, 1998

Form # 1: Name Paul G. Steffes NRA # 95-OSS-05

PLANETARY ASTRONOMY AND
ATMOSPHERES PROGRAMS

Log No.

Date Received:

NRA #: 95-OSS-05 Grant/Contract/RTOP #: NAGW - 533

Date Submitted: April 14, 1995

Please check all boxes appropriate to this NRA:

- o Planetary Astronomy
- ✓ Planetary Atmospheres
- o Major Equipment
- o Full Proposal: New Research
- ✓ Full Proposal: Renew Ongoing Research
- o Progress Proposal

For Planetary Astronomy Research Areas (please check only the one box that indicates the primary intent of the proposal)

- o Inner Planets
- o Outer Planets
- o Small Bodies (Asteroids, Comets, etc.)
- o Facility Support/Instrumentation

For Planetary Atmospheres Research Areas (please check only the one box that indicates the primary intent of the proposal)

- o Structure/Composition
- o Dynamics
- o Particles/Aerosols
- o Radiative Transfer
- ✓ Molecular Properties/Spectra
- o Aeronomy/Theory
- o Aeronomy/Energy Deposition
- o Aeronomy/Chemistry
- o Solar Wind Interaction

Form # 1, pg. 2: Name Paul G. Steffes NRA # 95-OSS-05

Type of Organization: UNIVERSITY
Profit, non-profit, university, etc.)

Proposal Title: LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

Principal Investigator (Name): PAUL G. STEFFES

Institution: GEORGIA INSTITUTE OF TECHNOLOGY

Address: SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GA 30332-0250

Telephone: (404) 894-3128 Fax: (404) 853-9171

E-Mail Address: ps11@prism.gatech.edu

Signature Paul G. Steffes Date 11 APR 1995

Institutional Authorization Official: JANIS L. GODDARD,
CONTRACTING OFFICER

Signature ______ Date 4/11/95

Address: GEORGIA TECH RESEARCH CORPORATION
OCA/PID
GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GA 30332-0420

Telephone: (404) 894-4817 Fax: (404) 894-6956

E-Mail Address: janis.goddard@oca.gatech.edu

Form #2: **Name: Paul G. Steffes** **NRA #95-0SS-05**

B. COGNIZANT PERSONNEL

For scientific or technical matters relating to the grant (Principal Investigator):

Paul G. Steffes
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0250
Telephone: (404) 894-3128
email: ps11@prism.gatech.edu

For contractual and business matters:

Georgia Tech Research Corporation
ATTN: Janis L. Goddard
Georgia Institute of Technology
Atlanta, GA 30332-0420
Telephone: (404) 894-4817
Fax: (404) 894-6956

(There are no Co-Investigators for this Grant.)

Proposed Project Duration: 36 months

Start date: November 1, 1995

End date: October 31, 1998

Budget Request:	Year 1	Year 2	Year 3
	$72,027	$72,027	$72,027

Total Funding Requested (3 years): $216,081

Form #3: Paul G. Steffes NRA 95-0SS-05 Grant #:NAGW-533

C. PROPOSAL SUMMARY

TITLE: Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres

PRINCIPAL INVESTIGATOR: Paul G. Steffes (Georgia Institute of Technology)

FIRST-YEAR REQUESTED FUNDS (FY96): $72,027 (November 1, 1995-October 31, 1996)

ABSTRACT

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave and millimeter-wave absorbing constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements and to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

In the currently completed grant year (November 1, 1995-October 31, 1995), we have applied our recently completed laboratory measurements of the microwave properties of H_2S under simulated Jovian planetary conditions to results from the Voyager radio occultation studies at Neptune and to microwave radiative transfer models of all Jovian planets. We have also completed laboratory measurements of the microwave absorption and refraction of SO_2, using our new computer-based measurement system. These results have been used in interpreting both microwave emission measurements of Venus and results from the Magellan atmospheric radio occultation studies (An appended package contains pertinent reprints and preprints from this work.)

The key activities proposed over the new three-year grant cycle include:

1. High accuracy laboratory measurement of the microwave absorptive and refractive properties of gaseous H_2SO_4, under simulated Venus conditions, and development of a new formalism describing these properties.
2. Application of the new H_2SO_4 formalism, and that for SO_2 to the two frequency Magellan radio occultation results so as to obtain highly accurate (localized) profiles of H_2SO_4 (g) and SO_2 abundance in the Venus atmosphere. Also apply to radiative transfer models for Venus microwave emission, and in the future to results from Venus Multiprobe Mission (VMPM).
3. Conduct VLA observations of Venus at 1.3 cm and 2 cm, and interpret results using the above formalisms, so as to characterize spatial and temporal variations in the abundances and distribution of H_2SO_4 (g) and SO_2.
4. High accuracy laboratory measurement of the microwave absorptive and refractive properties of phosphine (PH_3) under conditions for the Jovian planets. Apply results to existing Voyager radio occultation profiles from Saturn and Neptune. Also apply to radiative transfer models used to interpret radio astronomical observations of Jovian planets. Future applications will include Cassini radioscience.

(An appended package contains pertinent reprints and preprints as instructed in the NRA.)

Form #4: D. FULL BUDGET SUMMARY (Grant #NAGW-533) (NRA 95-0SS-05)

PRINCIPAL INVESTIGATOR: Paul G. Steffes (Georgia Institute of Technology)

TITLE: Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres

GRANT NUMBER: NAGW-533
For the period of November 1, 1995 through October 31, 1998 (3-year program)

ESTIMATED COST BREAKDOWN

I.	DIRECT SALARIES AND WAGES*:		$125,949
	A. Principal Investigator P.G. Steffes 25% time, 3 calendar years (.75 person-years)	$71,349	
	B. 1 Graduate Student (S.H. Suleiman) 50% time, 3 calendar years (1.5 person-years)	$45,000	
	C. 1 Sr. Admin. Secretary 12% time, 3 calendar years (.36 person-years)	$ 9,600	
II.	FRINGE BENEFITS**: 24.7% of Direct Salaries & Wages (less students)		$ 19,995
III.	MATERIALS, SUPPLIES, AND SERVICES		$ 4,500
A.	Gases, liquids, and supplies (microwave connectors and o-rings) for Experiments	$ 2,700	
B.	Miscellaneous Project Supplies (data storage media) and page charges	$ 1,800	
IV.	TRAVEL		$ 3,900
A.	Travel for Student to AAS/DPS Meetings: Tucson, Cambridge, Austin (each 5 days duration, airfare $600 plus registration and $ 100/day)	$3,900	
	SUBTOTAL - ESTIMATE OF DIRECT COSTS:		$154,344
V.	OVERHEAD (Indirect Expense)**: 40% of Modified Total Direct Cost Base		$ 61,737
	TOTAL BUDGET FOR THREE YEARS REQUESTED FROM NASA:		$216,081

SUMMARY OF STAFFING REQUEST: SEE SECTION I (ABOVE)

*The salary and wage rates are based on projected FY96 salaries for the Georgia Institute of Technology. The Georgia Tech Fiscal Year is July 1 through June 30.
**Rates are for the period July 1, 1994 through June 30, 1995 and are subject to adjustment upon DCAA audit and ONR negotiations.

Form #5: **E. FIRST-YEAR BUDGET SUMMARY (Grant #NAGW-533) (NRA 95-0SS-05)**

PRINCIPAL INVESTIGATOR: Paul G. Steffes (Georgia Institute of Technology)

TITLE: Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres

GRANT NUMBER: NAGW-533
For the period of November 1, 1995 through
October 31, 1996 (First year of 3-year program)

ESTIMATED COST BREAKDOWN

I.	DIRECT SALARIES AND WAGES*:		$41,983
	A. Principal Investigator P.G. Steffes 25% time, calendar year (.25 person-years)	$23,783	
	B. 1 Graduate Student (S.H. Suleiman) 50% time, calendar year (.5 person-years)	$15,000	
	C. 1 Sr. Admin. Secretary 12% time, calendar year (.12 person-years)	$ 3,200	
II.	FRINGE BENEFITS**: 24.7% of Direct Salaries & Wages (less students)		$ 6,665
III.	MATERIALS, SUPPLIES, AND SERVICES		$ 1,500
A.	Gases, liquids, and supplies (microwave connectors and o-rings) for Experiments	$ 900	
B.	Miscellaneous Project Supplies (data storage media) and page charges	$ 600	
IV.	TRAVEL		$ 1,300
A.	Travel for Student to AAS/DPS Meeting (Tucson, AZ, 5 days duration, airfare $600 plus registration and $ 100/day)	$ 1,300	
	SUBTOTAL - ESTIMATE OF DIRECT COSTS:		$51,448
V.	OVERHEAD (Indirect Expense)**: 40% of Modified Total Direct Cost Base		$20,579
	TOTAL FIRST YEAR BUDGET REQUESTED FROM NASA:		$72,027

SUMMARY OF STAFFING REQUEST: SEE SECTION I (ABOVE)

*The salary and wage rates are based on projected FY96 salaries for the Georgia Institute of Technology. The Georgia Tech Fiscal Year is July 1 through June 30.
**Rates are for the period July 1, 1994 through June 30, 1995 and are subject to adjustment upon DCAA audit and ONR negotiations.

Form #6: Name: Paul G. Steffes NRA# 95-OSS-05

F. LIST OF CURRENT AND PENDING RESEARCH SUPPORT FOR PRINCIPAL INVESTIGATOR

A. Current Support

1. National Aeronautics and Space Administration - Grant NAGW-533, "Laboratory Evaluation and Application of Microwave Absorption Properties under Simulated Conditions for Planetary Atmospheres," $67,624 for 12-month period (11/1/94-10/31/95). P.I. time commitment: 24% (3 person-months). (THIS PROPOSAL IS FOR RENEWAL OF THIS GRANT.)

2. National Aeronautics and Space Administration, Lewis Research Center - Contract NAS3-27361, "RF Propagation Effects and ACTS Satellite Channel Characterization for Very Small Aperture Terminals," $48,187 (portion of overall contract covering this P.I.) for 16-month period (8/10/94-12/09/95). P.I. time commitment: 8% (1.3 person months)

B. Pending Support (other than this proposal):

(None)

G. TABLE OF CONTENTS

COVER PAGES:

I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or using laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. For example, laboratory measurements completed recently by DeBoer and Steffes (1994, appended) under this grant (NAGW-533), have shown that the opacity from H_2S under simulated conditions for the outer planets is best described by a different lineshape than was previously used in theoretical predictions. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements and to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

II. VENUS STUDIES

A. Requirements for Laboratory Measurements

Over the past four years, we have been active in using the Magellan spacecraft to probe the Venus atmosphere by way of radio occultation studies. Descriptions and results of the October 1991 experiments, which included three radio occultations probing down to the 33 km altitude level at approximately 60°N latitude and 110° solar zenith angle (early evening), appeared in the July 1994 issue of Icarus (Steffes et al., 1994 and Jenkins et al., 1994). Processing of data taken over Venus' southern hemisphere in December 1992 (two profiles) is currently being completed by J. Jenkins (SETI Institute/NASAAmes) under the now-terminated VDAP program. We also assisted in the planning and conduct of a final campaign of Magellan radio occultation experiments (1994), which will produce an additional 15 profiles of atmospheric radio absorptivity and refractivity for the polar and mid-latitude regions. (These are currently being reduced by Jenkins and Hinson, with support from the Planetary Atmospheres Program.)

One key aspect of the Magellan radio occultation results is the high percentage accuracy of the measured profiles of 13 cm and 3.6 cm absorptivity; typically ±10-15% (See Figure 1.). This compares with uncertainties of ±80% for similar profiles from Pioneer-Venus occultation experiments (Jenkins and Steffes, 1991). To take advantage of these new profiles, so as to develop highly accurate abundance profiles of the microwave absorbing constituents, one must know the microwave absorbing and refracting properties of the constituents very accurately. Carbon dioxide (CO_2) is only a minor contributor to the microwave absorption at both

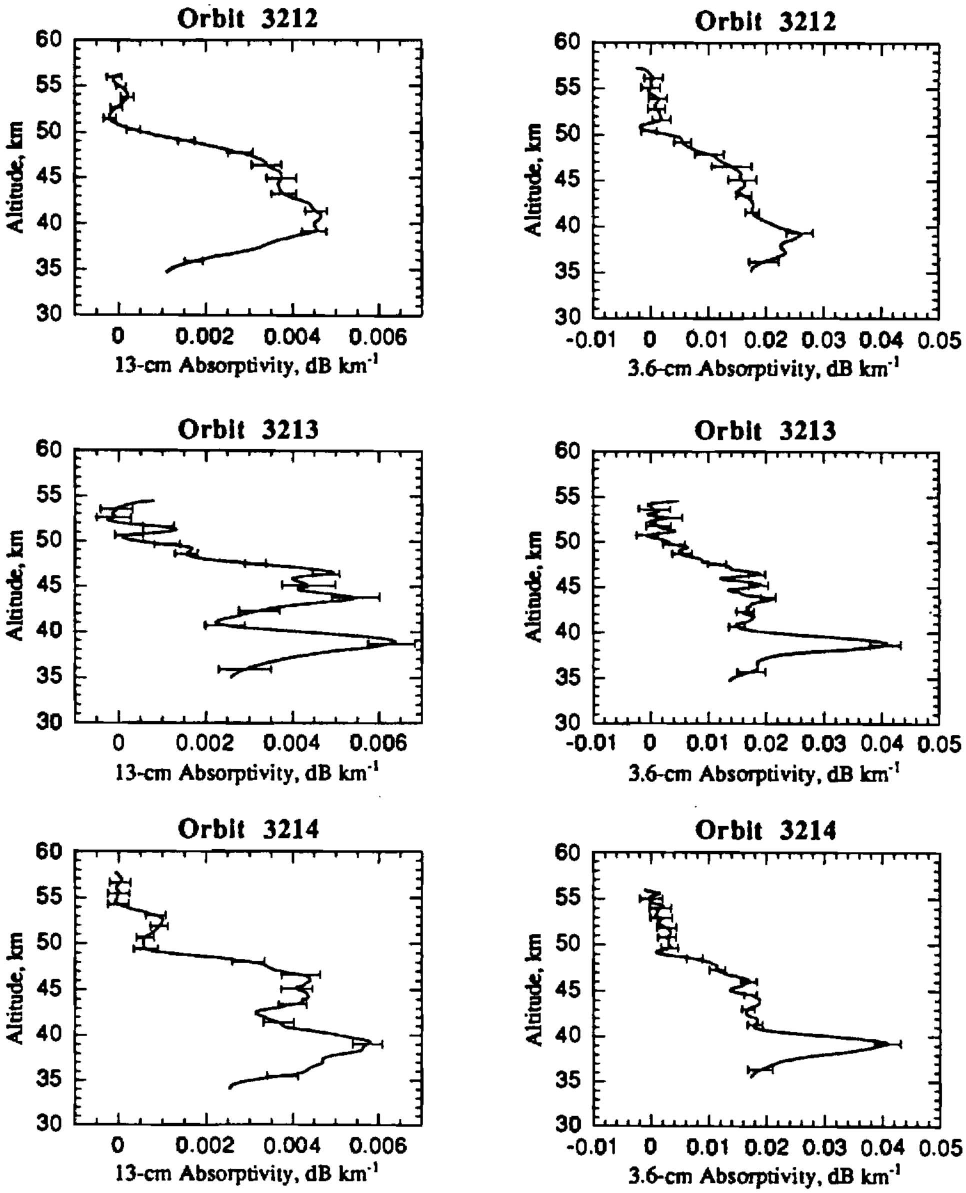


Figure 1: Profiles of 13-cm and 3.6-cm absorptivity measured by the October 1991 Magellan radio occultation experiment (Jenkins et al., 1994). Note the very small uncertainties.

wavelengths, but its absorption properties are well understood (Ho et al., 1966); and since its abundance does not vary significantly in the Venus atmosphere, its effects can be directly subtracted. At 13 cm, the remaining opacity is almost all due to gaseous sulfuric acid (H_2SO_4). Sulfuric acid is, of course, the predominant constituent in the Venus clouds. Understanding the spatial and temporal variations in its gas-phase abundance gives insight into the dynamical processes which affect cloud formation, as well as into the thermochemical processes which constrain the abundances of other reactive constituents in the Venus atmosphere such as COS, H_2O, CO, SO_2, and SO_3. Krasnopolsky and Pollack (1994) found that relatively small changes in the sub-cloud abundance of gaseous H_2SO_4 (from 5 ppm to 10 ppm) drops the putative cloud base altitude from 48.4 km to 46.5 km and raises the modelled H_2O abundance at the 30 km altitude level from 30 ppm to 90 ppm. The Magellan 13 cm radio opacity data can certainly discern between these scenarios, but only if the expression relating 13 cm opacity to H_2SO_4 abundance is highly accurate. While significant headway has been made in developing a theoretically-derived line catalog of the microwave resonances of H_2SO_4 (see Poynter et al., 1994), large uncertainties in the broadening parameters of the 55, 563 microwave lines makes estimates of their combined opacity at 13 cm highly uncertain (~ factor of two).

The best laboratory characterization of the 13 cm opacity from gaseous H_2SO_4 was conducted under this grant in 1984. (Steffes, 1985) The measurements had accuracies of ±50% which far exceeded the accuracies of the opacity data at that time, and dramatically reduced the uncertainties (± factor-of-seven) of previous estimates of gaseous H_2SO_4 opacity. However, now that much better measurements of Venus atmospheric absorptivity have been made, better laboratory measurements are necessary. These improved laboratory measurements are necessary not only at 13 cm, but also at 3.6 cm. Since at 13 cm, nearly all of the non-CO_2 opacity is due to gaseous H_2SO_4, its abundance profiles can be obtained using only 13 cm measurements. However, the non-CO_2 absorptivity measured by the radio occultation experiments at 3.6 cm is due to both gaseous H_2SO_4 and SO_2. Thus, after an accurate abundance profile for gaseous H_2SO_4 is obtained from 13 cm data, then the effects of gaseous H_2SO_4 can be removed from the 3.6 cm absorptivity profile leaving only that absorption due to SO_2 (Jenkins et al., 1994). Thus, in order to obtain accurate SO_2 abundance profiles from the 3.6 cm absorptivity profiles, knowledge of the microwave absorption properties of gaseous H_2SO_4 at both 13 cm and 3.6 cm is required, in addition to very accurate knowledge of the microwave absorption properties of SO_2 at 3.6 cm.

In the currently completed grant year (November 1, 1994-October 31, 1995), we have completed a program to more accurately characterize the microwave absorption properties of sulfur dioxide (SO_2) in a CO_2 atmosphere, especially with regard to its temperature dependence under simulated Venus conditions. (See Suleiman et al, 1995, appended) Initially, we intended to focus on measurements around 22 GHz (approximately 1.38 cm), since our radiative transfer models and laboratory measurements have shown it to be one of the few wavelengths where gaseous H_2SO_4 opacity is relatively small, and SO_2 abundances could be deduced from emission measurements. However, the availability of highly accurate profiles of 3.6 cm opacity from the Magellan radio occultation experiments makes it possible to deduce SO_2 abundances at that wavelength, as well. Thus, we increased the scope of the measurement program to include 1.38 cm, 3.6 cm, and 13.3 cm wavelengths over temperature and pressure ranges corresponding to the Venus atmosphere. These measurements are described by Suleiman et al. (1995, appended) and were conducted using a newly developed computer-based measurement system (DeBoer and Steffes, 1995a, appended). These results are being applied both to our radiative transfer model for interpreting the microwave and millimeter-wave emission measurements of Venus, and to the Magellan 3.6 cm absorptivity profiles, in order to make more accurate estimates of SO_2 abundances. However, as mentioned previously, it is also necessary to have very accurate expressions for the absorption from gaseous H_2SO_4 at both 13 cm and 3.6 cm in order to accurately estimate SO_2 abundances from the Magellan 3.6 cm absorptivity profiles.

The recently completed measurements of SO_2 microwave absorptivity and refractivity, and the proposed measurements (below) of the microwave absorptivity and refractivity of gaseous H_2SO_4 will be useful not only in interpreting results from Magellan radio occultation experiments, but will also be useful in interpreting planned opacity measurements to be made with the recently selected "Discovery" mission, VMPM (Venus Multi-Probe Mission). VMPM would insert 16 probes into the Venus atmosphere with dual-frequency (3.6 cm and 13 cm) uplink capability. The measured profiles of opacity derived from these probe uplink signals could then be used in deriving abundances of H_2SO_4 (g) and SO_2. Likewise, the measurements will be applied to the interpretation of centimeter wavelength emission measurements of Venus, such as those disk-averaged measurements conducted by Steffes et al. (1990) from 1.3 to 3.6 cm, and to future VLA maps of the 1.3 and 2 cm emission from the Venus atmosphere.

Working with newly-obtained observational data sets, older observational data sets, and our laboratory results, we hope to answer the following key questions regarding sulfur chemistry and meteorology in the Venus atmosphere:

1. How do the vertical profiles of the abundance of gaseous H_2SO_4 vary with position and time in the Venus atmosphere? (Results will be based on our new laboratory results as applied to Magellan radio occultation profiles and to 2 cm radio emission maps.)

2. How do the vertical profiles of the abundance of SO_2 vary with position and time in the Venus atmosphere? (Results will be based on application of our recently completed laboratory results as applied to Magellan radio occultation profiles and to 1.3 cm radio emission maps.)

3. How do the variations and the structure of the above profiles correlate in time and position?

B. Proposed Laboratory Measurements (Venus)

The approach to be used in measuring the microwave absorptivity of gaseous H_2SO_4 in a CO_2 atmosphere is similar to those previously used by DeBoer and Steffes (1994, appended) for the absorptivity of H_2S in an H_2/He atmosphere, and by Suleiman et al. (1995, appended) for the absorptivity of SO_2 in a CO_2 atmosphere under simulated Venus conditions, except that a flask of liquid H_2SO_4 is used to generate the H_2SO_4 vapor, when heated. As can be seen in Figure 2, the

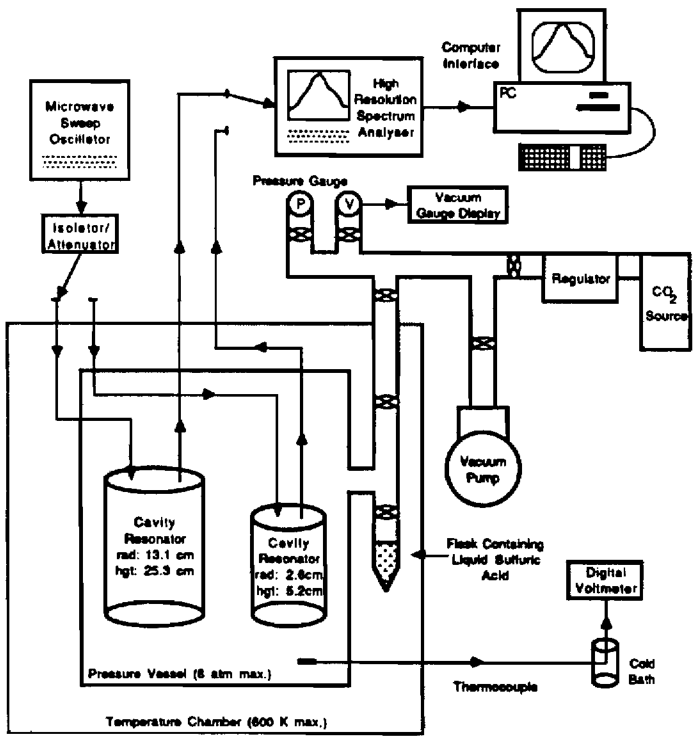


FIGURE 2:
Block diagram of the atmospheric simulator, as configured for measurements of the microwave absorption of gaseous sulfuric acid under Venus atmospheric conditions.

absorptivity of the gas mixture is measured by observing the effects of the introduced gas mixture on the Q, or quality factor, of the particular resonances of the two resonators contained in the pressure vessel. The changes in the Q are monitored by the computer-controlled spectrum analysis system, since Q is simply the ratio of the resonant frequency to the half-power bandwidth. Note also that changes in the resonant frequencies themselves are related to the refractivities of the gas mixture at those resonant frequencies, and is likewise important information for the proper interpretation of radio occultation data.

A complete analysis of the uncertainties associated with this measurement technique is given in the appended papers by DeBoer and Steffes (1994, appended) and by Suleiman et al. (1995, appended). However, one key issue is the uncertainty in the H_2SO_4 mixing ratio within the CO_2/H_2SO_4 gas mixture being tested.

As in our previous work with gaseous H_2SO_4 (Steffes, 1985, 1986), we will create a CO_2/H_2SO_4 mixture by first loading a precisely known volume of liquid H_2SO_4 into the sample flask and then heating the temperature chamber containing the pressure vessel and flask to a point near the highest possible operating temperature of the chamber (~590K). This assures the largest possible H_2SO_4 mixing ratio, since it is the vapor which evaporates from the liquid H_2SO_4 which will form part of the mixture. Once the entire system is uniformly heated (which requires approximately six hours) and thermal stability is reached, a vacuum is drawn in the pressure vessel containing the microwave cavity resonators, and the bandwidths and center frequencies of the resonances are then measured. For this experiment, resonances at 2.24 GHz (13.4 cm), 8.50 GHz (3.5 cm), 15.5 GHz (2 cm) and 21.7 GHz (1.38 cm) will be used. The 13.4 cm and 3.6 cm resonances are selected based on their proximity to the Magellan radio occultation wavelengths. The 2 cm and 1.38 cm resonances are selected based on their proximity to the VLA wavelengths most useful for probing the Venus atmosphere (see Section C, below). Next, a valve is opened allowing the sulfuric acid vapor eluting from the flask to fill the pressure vessel (31 liters open volume) and reach vapor pressure equilibrium with the liquid. It is then possible to measure the refractive index of the gaseous H_2SO_4 and the accompanying decomposition products (SO_3 and H_2O) by measuring changes in the resonance frequencies. Subsequently, CO_2 is admitted to the chamber (at a low rate so as not to significantly affect the temperature of the chamber) and the bandwidth and center frequency of each resonance is measured. Initially a total pressure of 6 Bars will be used, but lower pressures of the same mixture can be achieved by venting to 4 Bars and 2 Bars. The system will then be vented and filled with pure CO_2 at pressures giving the same refractive indices as the CO_2/H_2SO_4 mixtures (so as to avoid the effects of "dielectric loading", see DeBoer and Steffes, 1994, appended). By comparing the quality factors of the CO_2/H_2SO_4 mixture with the pure CO_2, the absorptivity of the gaseous H_2SO_4 can be determined. However, knowledge of its precise mixing ratio is necessary in order to develop expressions relating its absorptivity to its mixing ratio in a CO_2 atmosphere. Thus we precisely measure the amount of liquid acid remaining in the sample flask, and compute the abundance of gas phase H_2SO_4 by using dissociation constants from Vermeulen et al. (1984).

In past experiments, one large source of uncertainty rose from potential changes in the concentration of the acid reservoir, which made determination of the actual amount of sulfuric acid vapor difficult. In the new experiments, we will reduce this uncertainty in two ways. First, we will use a liquid sulfuric acid solution which is at the azeotropic concentration level (98.01%). This will not only assure maximum vapor pressure, but will also ensure no change in the concentration of the source liquid. Secondly, additional experiments will be conducted by allowing all liquid in the sample flask to vaporize, which will assure that changes in the concentration of the remaining acid in the reservoir will not result in erroneous sulfuric acid vapor abundance estimates.

In Table I, we compare the expected absorptivity from the CO_2/H_2SO_4 gas mixtures (derived from Van Vleck-Weisskopf theory, and using the newest line catalog from Poynter, Pickett, and Cohen, 1994) with the minimum detectable absorption from our system. While variations from the theoretical predictions by a factor of two are possible, it is clear that our new system can achieve the required ± 15% accuracy at 13 cm and 3.6 cm, at least at the higher pressures.

Table I

Expected Microwave Opacities of

H_2SO_4 vapor in a CO_2 environment

	2.25 GHz	8.52 GHz	15.2 GHz	21.7 GHz
T = 590 K				
H_2SO_4 vapor mixing ratio (best case) = 3.07 %				
Predicted absorption (dB/km)				
for P_{CO_2} = 6 atm:	2.02	15.75	27.99	28.79
P_{CO_2} = 4 atm:	1.55	10.43	17.46	15.60
P_{CO_2} = 2 atm:	0.75	5.18	7.92	5.60
System sensitivity (dB/km):	0.05	0.14	0.90	2.29
T = 590 K				
H_2SO_4 vapor mixing ratio (worst case) = 0.56 %				
Predicted absorption (dB/km)				
for P_{CO_2} = 6 atm:	0.37	2.87	5.11	5.25
P_{CO_2} = 4 atm:	0.28	1.90	3.19	2.85
P_{CO_2} = 2 atm:	0.14	0.94	1.44	1.02
System sensitivity (dB/km):	0.05	0.14	0.90	2.29

C. Applications to Observations and Radiative Transfer Modelling

Once laboratory measurements of the absorptivity and refractivity are completed, an analytical formalism will be developed, using the existing Poynter/Pickett/Cohen line catalog (1994), which will allow accurate computation of the opacity of the H_2SO_4 under Venus conditions. The formalism to be developed fits the laboratory data to the combined effects of all 55,563 lines by selecting the proper lineshape formalism (Van Vleck-Weisskopf, Ben Reuven, Gross, etc.), in a similar fashion to that used previously to develop formalisms for H_2S (DeBoer and Steffes, 1994, appended) and SO_2 (Suleiman, et al., 1995, appended).

The new formalism will be directly applied to the 13 cm Magellan absorptivity profiles shown in Figure 1 (after subtracting the known absorption from CO_2) to develop high accuracy H_2SO_4 abundance profiles for the Venus atmosphere. Additionally, by using the new profiles and our formalism, we can subtract the effects of the absorption of H_2SO_4 (and CO_2) from the 3.6 cm absorptivity profiles and be left with only absorption due to SO_2, which will then be used to derive SO_2 abundance profiles, using the new formalism we have developed for SO_2 opacity (Suleiman et al., 1995, appended). Details of the new H_2SO_4 formalism will, of course, be published and also provided to investigators working with Venus absorptivity data (e.g. Jenkins at SETI Institute/NASA Ames) so as to be used in developing their new results.

Of equal interest will be the application of this formalism to our microwave radiative transfer model for Venus. A new model for the microwave emission from Venus has been developed by Graduate Student Marc Kolodner, which is innovative in its full analysis of the effects of atmospheric refraction on limb emission and in its use of Magellan results for modelling the centimeter wavelength surface emission. The first application of this model is described in Suleiman et al. (1995, appended) where the model is used with the new formalism for SO_2 absorption to place limits on the abundance of SO_2 in the Venus atmosphere based on disk-averaged observations of the centimeter-wavelength emission (Steffes et al., 1990).

One key result of the new modelling effort is the determination that the 20-25 GHz range is the most sensitive portion of the Venus microwave emission spectrum to subcloud SO_2. This is significant in that it includes the 1.3 cm wavelength observable with the VLA. Thus, maps of the 1.3 cm Venus emission could be used to detect spatial variations in the abundance and distribution of SO_2. The only attempt to map the 1.3 cm Venus emission with the VLA was made by Janssen et al. (1982) in December 1981. Unfortunately, because of problems involving antenna beam size correction and the "immature" status of the VLA signal processing system at that time, images derived at both 1.3 cm and 2.0 cm had large noise levels ($\pm$ 10K or more) which would make detection of emission variations due to SO_2 abundance variations difficult. Similarly, based on our preliminary theoretical model for the opacity from gaseous H_2SO_4 (Van Vleck-Weisskopf line shapes using the Poynter, Pickett, and Cohen line catalog), it appears as if the 2 cm wavelength emission is especially sensitive to the sub-cloud abundance of gaseous H_2SO_4. (See Figure 3. Note that this was also suggested by earlier laboratory measurements by Steffes, 1986.) Thus, a new attempt to map Venus at both 1.3 cm (sensitive to SO_2) and 2 cm (sensitive to gaseous H_2SO_4) with the VLA be made. (Our target time for this observations is Winter 1996, when Venus size and VLA configuration will be optimal.) The emission maps will then be interpreted using our radiative transfer model incorporating the new formalisms for the opacity from SO_2 and gaseous H_2SO_4.

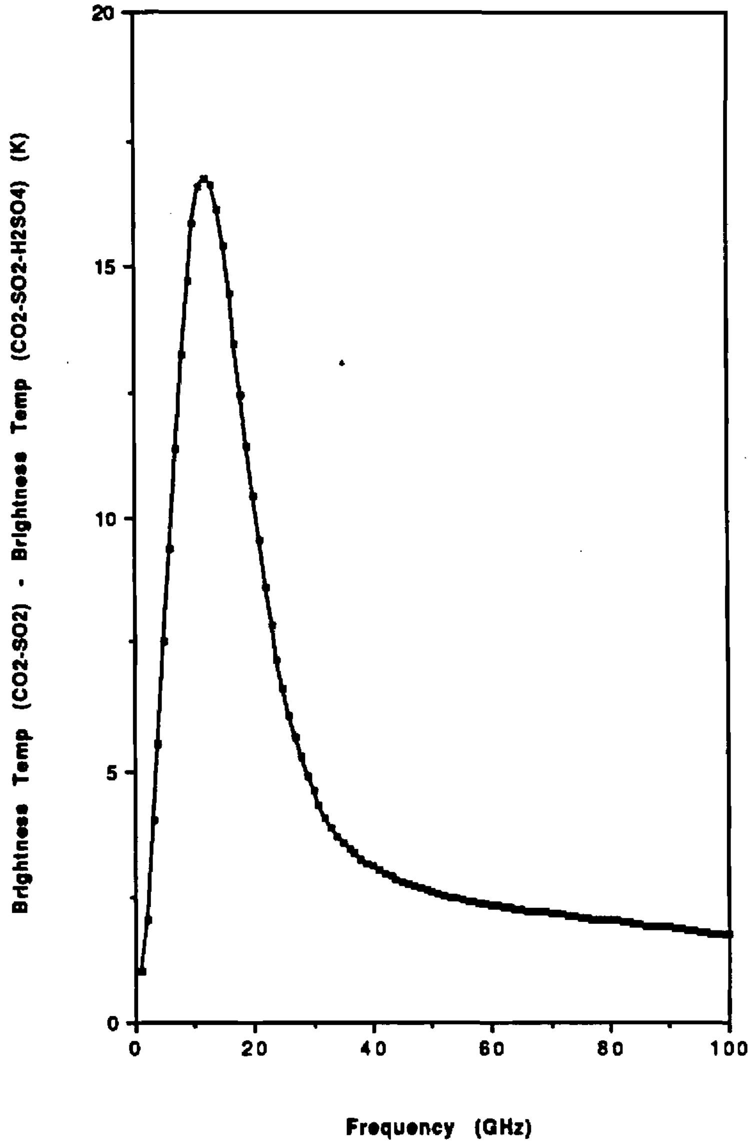


Figure 3: Expected darkening of Venus disk-averaged microwave spectrum due to a sub-cloud H2SO4(g) abundance of 20 ppm.

III. OUTER PLANETS STUDIES

As part of his dissertation research, Graduate Research Assistant David DeBoer has developed the most complete radiative transfer model for microwave emission from the Jovian planets yet developed (DeBoer, 1995). Focusing on Neptune, this work started with a new formalism for the opacity from H_2S developed from our laboratory measurements (DeBoer and Steffes, 1994, appended), but has included a number of other improvement including more accurate expressions for the saturation vapor pressure of H_2S, and a more thorough treatment of absorption and scattering by cloud particulates. (A condensed description of this radiative transfer model will be included in a new paper by DeBoer and Steffes, 1995b.).

In order to best match the most reliable disk-averaged emission measurements (1 mm to 20 cm) and <u>not</u> exceed the measurements of 13 cm and 3.6 cm absorptivity made by Voyage 2 at Neptune (Lindal, 1992), a Neptune atmosphere where the abundance of H_2S is greater that of NH_3 below the putative NH_4 SH cloud in the deep atmosphere is required. While such an atmosphere (e.g. 78% H_2, 19% He, 3% CH_4, plus 40 x solar H_2S and 0.2 x solar NH_3) gives an excellent fit to the microwave emission spectrum, its opacity is too low at 13 cm and 3.6 cm to explain the Voyager radio occultation results. It is possible, however, to match both emission spectra <u>and</u> the Voyager results by adding phosphine (PH_3) to the model.

Phosphine has been detected on Jupiter and Saturn at its strong rotational resonance (267 GHz, see Weisstein and Serabyn, 1994a,b). Preliminary estimates with our Neptune model suggest that a PH_3 abundance between 10x and 20x solar best fits the microwave data (DeBoer, 1995). Note that Weisstein and Serabyn (1994a) inferred a 10x solar abundance at Saturn. Estimates of the microwave absorption spectrum from PH_3 have been made using the updated Poynter, Pickett, and Cohen line catalog (1994). While some line intensities have been measured, many, including the weak inversion lines in the centimeter wavelength range, have not; and no measurements of line shape parameters have been made. However, by assuming the Van Vleck-Weisskopf lineshapes and a range of broadening parameters it is possible to set a range on the expected opacity. In Figure 4, we compare the opacity from an H_2/He/H_2S mixture used in our laboratory

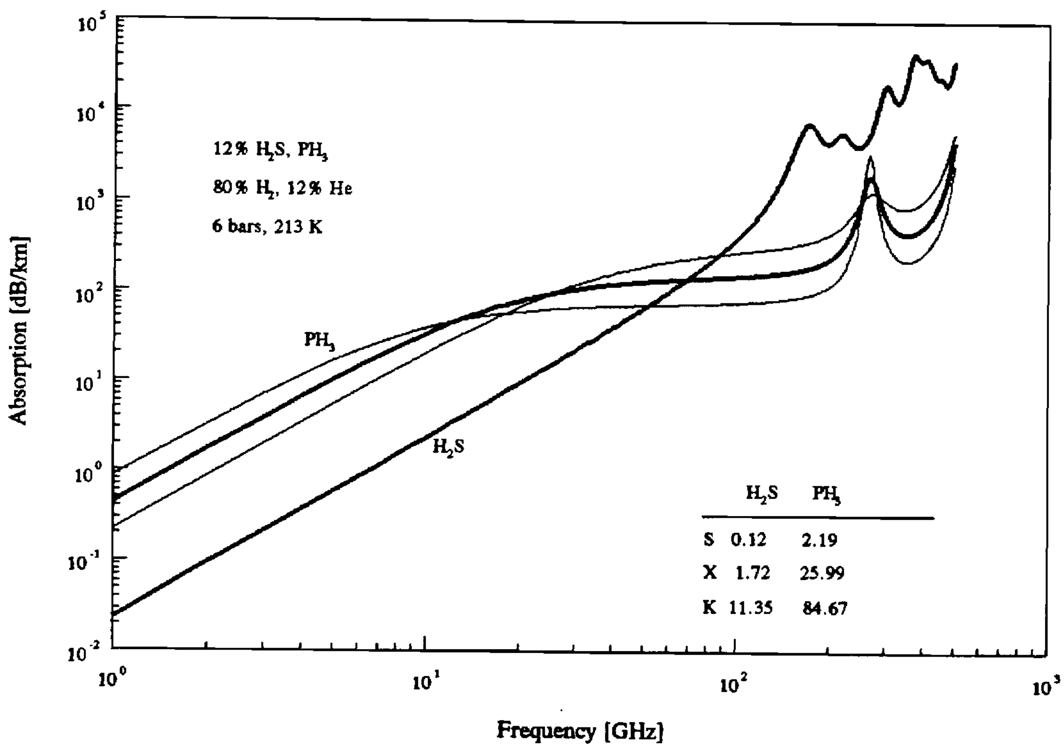


Figure 4: Predicted opacity from phosphine (PH3) in a Jovian-like atmosphere as compared with that from H2S. The thin lines esimate a range of possible phosphine opacity depending on line shape parameter.

measurements with that from an identical mixture which replaces H_2S with PH_3. This figure shows that the opacity from the mixture including PH_3 will far exceed the opacity from the H_2S mixtures we successfully measured previously (DeBoer and Steffes, 1994, appended). However, the actual opacity may vary by an order of magnitude depending on which lineshape parameters are used. Thus, to accurately infer the PH_3 abundance in Neptune's atmosphere from centimeter-wavelength microwave data, accurate laboratory measurements of its opacity (and refractivity) are necessary.

We propose to use the same system used previously by DeBoer and Steffes (1994, appended) to measure the opacity and refractivity of H_2S under simulated conditions for the outer planets. The opacity and refractivity of an $H_2/He/PH_3$ mixture will be measured at 2.25 GHz (13.3 cm), 8.5 GHz (3.7 cm) and 21.7 GHz (1.38 cm) at pressures from 1 to 6 Bars and at three temperatures from 150K to 298K. The results will be used to develop a formalism for PH_3 opacity which will be used in the interpretation of radio occultation derived absorptivity profiles at Neptune and will provide PH_3 abundance estimates. The formalism will also be applied to our radiative transfer model, so as to derive accurate estimates of PH_3 abundance from Neptune emission data.

IV. PROPOSED PROCEDURE AND LEVEL OF EFFECT

The proposed level of effort in the 3 year period proposed(November 1, 1995 through October 31, 1998) involves one professor (P.G. Steffes, Professor of Electrical and Computer Engineering) at 25% time, and one graduate student (Graduate Research Assistant Shady H. Suleiman) at 50% time, with supplies and other support as indicated in the attached cost breakdown (see Section VI). (Note that 50% is the maximum support level for Ph.D. students with the remaining 50% considered as registered academic thesis research.) In addition to the participation in the program by Professor Steffes and the paid graduate research assistant, contributions to the program from both graduate and undergraduate students working on special projects for academic credit have been substantial. One other Ph.D. student (Marc A. Kolodner, School of Physics) is conducting his Ph.D. research in the area of this grant with Georgia Tech support. Likewise, in the spirit of the NASA Graduate Student Researchers Program (Underrepresented Minority Focus), we continue to seek out talented underrepresented minority students and involve them in our program.

V. FACILITIES

The specific measurements described in this proposal will be conducted at the Radio Astronomy and Propagation Laboratory and the accompanying Remote Sensing Laboratory, which are located within the School of Electrical and Computer Engineering. A description of the equipment being used for these measurements has been given in the previous papers and reports. (e.g. DeBoer and Steffes, 1995a)

For support of any required data analysis and computing activities, a wide range of computing services for education, research, and administration is provided by the Georgia Tech Office of Informational Technology. Numerous personal computers are also available to support this project.

VI.a FIRST-YEAR BUDGET SUMMARY

PRINCIPAL INVESTIGATOR: Paul G. Steffes (Georgia Institute of Technology)

TITLE: Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres

GRANT NUMBER: NAGW-533
For the period of November 1, 1995 through
October 31, 1996 (First year of 3-year program)

ESTIMATED COST BREAKDOWN

I.	DIRECT SALARIES AND WAGES*:		$41,983
	A. Principal Investigator P.G. Steffes 25% time, calendar year (.25 person-years)	$23,783	
	B. 1 Graduate Student (S.H. Suleiman) 50% time, calendar year (.5 person-years)	$15,000	
	C. 1 Sr. Admin. Secretary 12% time, calendar year (.12 person-years)	$ 3,200	
II.	FRINGE BENEFITS**: 24.7% of Direct Salaries & Wages (less students)		$ 6,665
III.	MATERIALS, SUPPLIES, AND SERVICES		$ 1,500
A.	Gases, liquids, and supplies (microwave connectors and o-rings) for Experiments	$ 900	
B.	Miscellaneous Project Supplies (data storage media) and page charges	$ 600	
IV.	TRAVEL		$ 1,300
A.	Travel for Student to AAS/DPS Meeting (Tucson, AZ, 5 days duration, airfare $600 plus registration and $ 100/day)	$ 1,300	
	SUBTOTAL - ESTIMATE OF DIRECT COSTS:		$51,448
V.	OVERHEAD (Indirect Expense)**: 40% of Modified Total Direct Cost Base		$20,579
	TOTAL FIRST YEAR BUDGET REQUESTED FROM NASA:		$72,027

SUMMARY OF STAFFING REQUEST: SEE SECTION I (ABOVE)

*The salary and wage rates are based on projected FY96 salaries for the Georgia Institute of Technology. The Georgia Tech Fiscal Year is July 1 through June 30.
**Rates are for the period July 1, 1994 through June 30, 1995 and are subject to adjustment upon DCAA audit and ONR negotiations.

VI.b SECOND-YEAR BUDGET SUMMARY

PRINCIPAL INVESTIGATOR: Paul G. Steffes (Georgia Institute of Technology)

TITLE: Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres

GRANT NUMBER: NAGW-533
For the period of November 1, 1996 through
October 31, 1997 (Second year of 3-year program)

ESTIMATED COST BREAKDOWN

I.	DIRECT SALARIES AND WAGES*:		$41,983
	A. Principal Investigator P.G. Steffes 25% time, calendar year (.25 person-years)	$23,783	
	B. 1 Graduate Student (S.H. Suleiman) 50% time, calendar year (.5 person-years)	$15,000	
	C. 1 Sr. Admin. Secretary 12% time, calendar year (.12 person-years)	$ 3,200	
II.	FRINGE BENEFITS**: 24.7% of Direct Salaries & Wages (less students)		$ 6,665
III.	MATERIALS, SUPPLIES, AND SERVICES		$ 1,500
A.	Gases, liquids, and supplies (microwave connectors and o-rings) for Experiments	$ 900	
B.	Miscellaneous Project Supplies (data storage media) and page charges	$ 600	
IV.	TRAVEL		$ 1,300
A.	Travel for Student to AAS/DPS Meeting (Cambridge, MA, 5 days duration, airfare $600 plus registration and $ 100/day)	$ 1,300	
	SUBTOTAL - ESTIMATE OF DIRECT COSTS:		$51,448
V.	OVERHEAD (Indirect Expense)**: 40% of Modified Total Direct Cost Base		$20,579
	TOTAL SECOND YEAR BUDGET REQUESTED FROM NASA:		$72,027

SUMMARY OF STAFFING REQUEST: SEE SECTION I (ABOVE)

*The salary and wage rates are based on projected FY96 salaries for the Georgia Institute of Technology. The Georgia Tech Fiscal Year is July 1 through June 30.
**Rates are for the period July 1, 1994 through June 30, 1995 and are subject to adjustment upon DCAA audit and ONR negotiations.

VI.c THIRD-YEAR BUDGET SUMMARY

PRINCIPAL INVESTIGATOR: Paul G. Steffes (Georgia Institute of Technology)

TITLE: Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres

GRANT NUMBER: NAGW-533
For the period of November 1, 1997 through October 31, 1998 (Third year of 3-year program)

ESTIMATED COST BREAKDOWN

I.	DIRECT SALARIES AND WAGES*:		$41,983
	A. Principal Investigator P.G. Steffes 25% time, calendar year (.25 person-years)	$23,783	
	B. 1 Graduate Student (S.H. Suleiman) 50% time, calendar year (.5 person-years)	$15,000	
	C. 1 Sr. Admin. Secretary 12% time, calendar year (.12 person-years)	$ 3,200	
II.	FRINGE BENEFITS**: 24.7% of Direct Salaries & Wages (less students)		$ 6,665
III.	MATERIALS, SUPPLIES, AND SERVICES		$ 1,500
A.	Gases, liquids, and supplies (microwave connectors and o-rings) for Experiments	$ 900	
B.	Miscellaneous Project Supplies (data storage media) and page charges	$ 600	
IV.	TRAVEL		$ 1,300
A.	Travel for Student to AAS/DPS Meeting (Austin, TX, 5 days duration, airfare $600 plus registration and $ 100/day)	$ 1,300	
	SUBTOTAL - ESTIMATE OF DIRECT COSTS:		$51,448
V.	OVERHEAD (Indirect Expense)**: 40% of Modified Total Direct Cost Base		$20,579

TOTAL THIRD YEAR BUDGET REQUESTED FROM NASA: $72,027

SUMMARY OF STAFFING REQUEST: SEE SECTION I (ABOVE)

*The salary and wage rates are based on projected FY96 salaries for the Georgia Institute of Technology. The Georgia Tech Fiscal Year is July 1 through June 30.
**Rates are for the period July 1, 1994 through June 30, 1995 and are subject to adjustment upon DCAA audit and ONR negotiations.

VII. REFERENCES

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DeBoer, D.R. and P.G. Steffes, 1994. Laboratory measurements of the microwave properties of H_2S under simulated Jovian conditions with an application to Neptune. Icarus 109, 352-366. (Reprint appended)

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Weisstein, E.W. and E. Serabyn 1994b. Detection of the PH_3 J=3-2 rotational transition in Jupiter and Saturn. B.A.A.S. 26, 1108.

BIOGRAPHICAL SKETCH
PAUL G. STEFFES
PROFESSOR
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332-0250

EDUCATION

S.B.	Electrical Engineering	1977
S.M.	Electrical Engineering	1977
	Massachusetts Institute of Technology	
Ph.D.	Electrical Engineering	1982
	Stanford University	

EMPLOYMENT HISTORY

Massachusetts Institute of Technology, Research Laboratory of Electronics, Radio Astronomy and Remote Sensing Group
Graduate Research Assistant — 1976-1977

Watkins-Johnson Company, Sensor Development, San Jose, California
Member of the Technical Staff — 1977-1982

Stanford University, Electronics Laboratory, Center for Radar Astronomy, Stanford, California
Graduate Research Assistant — 1979-1982

Georgia Institute of Technology, School of Electrical Engineering, Atlanta, Georgia
Assistant Professor — 1982-1988
Associate Professor — 1988-1994
Professor — 1994-Present

EXPERIENCE SUMMARY

At Massachusetts Institute of Technology

Responsible for development, operation, and data analysis for an 8-channel, 118 GHz radiometer system flown aboard the NASA Flying Laboratory (CV-990) as an engineering model for a meteorological sensing satellite. Duties included hardware development of millimeter-wave, microwave, analog, and A to D segments of the system, in addition to airborne operation and reduction of data. The research resulted in a Master's thesis entitled "Atmospheric Absorption at 118 GHz," detailing the first airborne measurement of high altitude atmospheric absorption in the 2.5 millimeter wavelength range, due to atmospheric oxygen.

At Watkins-Johnson Company

Responsibilities included proposals and system design and development, particularly in the area of millimeter-wave systems. Responsibility for millimeter-wave systems development included government sponsored study and development of ELINT (Electronic Intelligence) and radar warning receiving systems to frequencies as high as 110 GHz, as well as internal company sponsored development projects including a 60 GHz communications system and millimeter-wave downconverters.

At Stanford University

Research was concentrated in the area of microwave radio occultation experiments from Voyager and Mariner spacecraft, with specific interest in microwave absorption in planetary atmospheres. Work included computer-based theoretical development of microwave absorption coefficients for planetary atmospheres, to facilitate the use of radio occultation-derived microwave absorption profiles in determining constituent densities. Additional work included the development of a fully instrumented experimental facility for use in measuring the microwave properties of planetary atmospheres under simulated planetary conditions. The research resulted in a Ph.D. dissertation entitled "Abundances of Cloud-Related Gases in the Venus Atmosphere as Inferred from Observed Radio Opacity."

At Georgia Tech

Research Activities: Principal Investigator of the National Science Foundation Grant, "Remote Sensing of Clouds Bearing Acid Rain." This research studied and designed a microwave/millimeter-wave system for remotely sensing the pH of acidic clouds (1982-1983). Principal Investigator of the NASA Planetary Atmospheres Program, "Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres." This research includes study of the interaction between atmospheric constituents and electromagnetic waves, along with application of these studies to spacecraft and radio telescopic measurements of the microwave absorption in atmospheres of Venus and the outer planets (1984-1995). Principal Investigator of the GTE Spacenet Program, "Satellite Interference Locating System (SILS)." The program involved location of uplink signals on the surface of the earth without disrupting regular satellite operations (1986-1990). Principal Investigator of the Emory University/Georgia Tech Biomedical Technology Research Center project, "Research in Development of a Non-Invasive Blood Glucose Monitoring Technique." This research involved the use of active infrared systems to determine glucose levels in the human eye and bloodstream (1988-1989), with subsequent support (1990-1991) from Lifescan, Inc. Principal Investigator of the NASA Pioneer Venus Guest Investigator Program, "Pioneer Venus Radio Occultation (ORO) Data Reduction: Profiles of 13 cm Absorptivity." This research inferred 13 cm wavelength absorptivity profiles using the Pioneer Venus Orbiter, and then used such profiles to characterize abundance profiles for gaseous H_2SO_4 in the Venus atmosphere (1988-1990). Principal Investigator/Team Member of NASA High Resolution Microwave Survey (HRMS). This research involved development and operation of the world's most sensitive receiving system used for a 1-10 GHz Sky Survey (1991-1994). Developer of atmospheric radio occultation experiments conducted with the Magellan (Venus) Spacecraft (1991-1994). Director of the Ku Band Satellite Earth Station System. Responsible for development of a Ku-band uplink/downlink system for use in inter-university networks (1985-1995). Principal investigator in the NASA/ACTS Propagation Experiments Program (1994-1995). This research involves study of Ka-Band propagation effects.

Teaching Activities: Resource Professor for "Satellite Communications Systems" (graduate course) and "Electromagnetics III" (undergraduate required course covering waves, waveguides, and antennas). Have also taught "Electromagnetics II" (electrodynamics), "Signals and Systems," and "Survey of Remote Sensing."

Administrative Activities: Chairman, School of ECE Electromagnetics Technical Group, 1990-1995.

HONORS AND AWARDS

Member, Eta Kappa Nu.
Member, Sigma Xi.
Senior Member, IEEE (Member of 6 IEEE Societies).
Recipient of the Stewart Award (MIT for exceptional contribution to student extra-curricular life, 1977.
Recipient of the Metro Atlanta Young Engineer of the Year Award, presented by the Society of Professional Engineers, 1985.
Recipient of the Sigma Xi Young Faculty Research Award, 1988.
Associate Editor, Journal.for Geophysical Research (JGR-Atmospheres), 1984-1989.
Appointed Member of the NASA Management and Operations Working Group for the Planetary Atmospheres Program (1986-1990).
Elected to the Electromagnetics Academy, October 1990.
Recipient of the Sigma Xi Best Faculty Paper Award, 1991.
Recipient of the NASA Group Achievement Award, "For outstanding contribution to the design, development, and operation of the High Resolution Microwave Survey Project, and its successful inauguration," March 1993.

OTHER PROFESSIONAL AFFILIATIONS

Member, American Association for the Advancement of Science.
Member, American Astronomical Society, Division for Planetary Sciences.
Member, American Geophysical Union.
Member, American Institute of Physics.
Member, American Society for Engineering Education.
Chairman, Atlanta Chapter, IEEE Antennas and Propagation Society and Microwave Theory and Techniques Society, 1986-1988. Director, IEEE Atlanta Section, 1988-1989.
Georgia Tech Chapter, Sigma Xi, Vice President, 1990-1991; President 1991-1992; Past-President, 1992-1993.
Chairman, Publicity Committee, 1993 IEEE International Microwave Symposium.

OTHER PROFESSIONAL ACTIVITIES

Proposal Reviewer for the NASA Planetary Astronomy Program, the NASA Planetary Atmospheres Program, the NASA Planetary Instrument Definition and Development Program, the NASA Voyager Data Analysis Programs, the NASA Exobiology Program, and the NSF Communications Research Program.
Reviewer/Referee for Icarus (International Journal of Solar System Studies), Journal of Geophysical Research, Radioscience, IEEE Microwave and Guided Wave Letters, and for several textbooks in the area of electromagnetics.
Consultant to industry in the areas of microwave, millimeter-wave, and RF systems for

communications, detection, and monitoring. This includes satellite communications, antenna systems, and propagation.
Expert witness in cases involving antenna/communications system performance, and the effects of environmental factors on such systems.

PATENTS

E. H. Orr and P. G. Steffes, "Method and System for Detecting Water Depth and Piloting Vessels," Patent # 4,757,481, issued July 12, 1988.

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FEBRUARY 1995

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N/A

GEORGIA TECH RESEARCH CORPORATION

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Refer to: JG/02.105.002.97.001

10 July 1996

NASA Headquarters
Planetary Atmospheres Program
Code SR
Washington, DC 20546-0001

Attention: Dr. Jay T. Bergstralh

Subject: Research Proposal and Progress Report Entitled, "Laboratory Evaluation and Application of Microwave Absorption Properties under Simulated Conditions for Planetary Atmospheres"

Reference: Grant No. NAGW-533

Dear Dr. Bergstralh:

The GEORGIA TECH RESEARCH CORPORATION desires to submit for your consideration the subject proposal prepared by Dr. Paul G. Steffes, School of Electrical and Computer Engineering, Georgia Institute of Technology. Should additional information be desired, please do not hesitate to contact Dr. Steffes at 404/894-3128 regarding technical matters or the undersigned at 404/894-4817 for administrative concerns.

In the event of an award, we propose that the work be authorized by a supplement to the referenced grant.

We appreciate the opportunity of submitting this proposal and look forward to continuing work with you on this project.

Sincerely,

Janis L. Goddard
Contracting Officer

JG/nz

Addressee: Two copies
Enclosure: Proposal - two copies

RENEWAL PROPOSAL
AND
PROGRESS REPORT #22

ENTITLED

LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

to the

Planetary Atmospheres Program of the
National Aeronautics and Space Administration
for Grant NAGW-533

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Report Period: November 1, 1995 through October 31, 1996

Proposed Renewal Period: November 1, 1996 through October 31, 1997

Submitted: July 1996

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I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occulation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or using laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. For example, laboratory measurements completed recently by Suleiman et al. (1996 reprints previously mailed) under this grant (NAGW-533), have shown that the opacity from, SO_2 under simulated Venus conditions is best described by a different lineshape than was previously used in theoretical predictions. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements and to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

II. PROGRESS REPORT

A. Laboratory Measurements under Simulated Venus Conditions

Over the past five years, we have been active in using the Magellan spacecraft to probe the Venus atmosphere by way of radio occultation studies. One key aspect of the Magellan radio occultation results is the high percentage accuracy of the measured profiles of 13 cm and 3.6 cm absorptivity; typically $\pm$10-15%. To take advantage of these new profiles, so as to develop highly accurate abundance profiles of the microwave absorbing constituents, one must know the microwave absorbing and refracting properties of the constituents very accurately. Carbon dioxide (CO_2) is only a minor contributor to the microwave absorption at both wavelengths, but its absorption properties are well understood (Ho et al., 1966); and since its abundance does not vary significantly in the Venus atmosphere, its effects can be directly subtracted. At 13 cm, the remaining opacity is almost all due to gaseous sulfuric acid (H_2SO_4). Sulfuric acid is, of course, the predominant constituent in the Venus clouds. Understanding the spatial and temporal variations in its gas-phase abundance gives insight into the dynamical processes which affect cloud formation, as well as into the thermochemical processes which constrain the abundances of other reactive constituents in the Venus atmosphere such as COS, H_2O, CO, SO_2, and SO_3. While significant headway has been made in developing a theoretically-derived line catalog of the microwave resonances of H_2SO_4 (see Poynter et al., 1994), large uncertainties in the broadening parameters of the 55,563 microwave lines makes estimates of their combined opacity at 13 cm highly uncertain (~ factor of two).

The best laboratory characterization of the 13 cm opacity from gaseous H_2SO_4 was conducted under this grant in 1984. (Steffes, 1985) The measurements had accuracies of $\pm$50% which far exceeded the accuracies of the opacity data at that time, and dramatically reduced the uncertainties ($\pm$ factor-of-seven) of previous estimates of gaseous H_2SO_4 opacity. However, now that much better measurements of Venus atmospheric absorptivity have been made, better laboratory measurements are necessary.

In the currently completed grant year (November 1, 1995 - October 31, 1996), we have begun a program to more accurately characterize the microwave absorption properties of sulfuric acid vapor (H_2SO_4) in a CO_2 atmosphere. The approach used in measuring the microwave absorptivity of gaseous H_2SO_4 in a CO_2 atmosphere is similar to those previously used by Suleiman et al. (1996) for the absorptivity of SO_2 in a CO_2 atmosphere under simulated Venus conditions, except that a flask of liquid H_2SO_4 is used to generate the H_2SO_4 vapor, when heated. As can be seen in Figure 1, the absorptivity of the gas mixture is measured by observing the effects of the introduced gas mixture on the Q, or quality factor, of the particular resonances of the two resonators contained in the pressure vessel. The changes in the Q are monitored by the computer-controlled spectrum analysis system, since Q is simply the ratio of the resonant frequency to the half-power bandwidth. Note also that changes in the resonant frequencies themselves are related to the refractivities of the gas mixture at those resonant frequencies, and is likewise important information for the proper interpretation of radio occultation data.

As in our previous work with gaseous H_2SO_4 (Steffes, 1985, 1986), we create a CO_2 / H_2SO_4 mixture by first loading a precisely known volume of liquid H_2SO_4 into the sample flask and then heating the temperature chamber containing the pressure vessel and flask to a high operating temperature (~ 560K). This assures a large mixing ratio, since it is the vapor which evaporates from the liquid H_2SO_4 which will form part of the mixture. In past experiments, one large source of uncertainty rose from potential changes in the H_2SO_4 mixing ratio caused by reactions with the silver plating on the resonators, which made determination of the actual amount of sulfuric acid vapor difficult. In the new experiments, we have used gold-plated resonators, thus eliminating the effects of reactions.

In Figure 2, the results from the initial absorptivity measurements are shown. These absorptivities are normalized by the sulfuric acid mixing ratio in a CO_2 atmosphere. Additional measurements will be completed by August 1996, so as to develop the most accurate formalism for H_2SO_4 opacity.

B. Venus Observations and Radiative Transfer Modelling

In October 1995, a proposal was submitted to the National Radio Astronomy Observatory (NRAO) for use of the Very Large Array (VLA) for mapping the 1.3 cm and 2 cm emission from Venus. (See Appendix A.) These wavelengths were chosen since they are especially sensitive to the opacity from SO_2 (1.3 cm) and H_2SO_4(2 cm). (See Suleiman et al., 1996 and Kolodner and Steffes, 1995.) The observations were conducted on April 5, 1996 by graduate students Shady H. Suleiman and Marc A. Kolodner, assisted by Dr. Brian Butler from NRAO. Initial inspection of the maps derived from these observations (See Figures 3 and 4) show darkened regions at latitudes greater than 60 degrees. These darkened regions are larger and more pronounced than simple "limb darkened" zones expected from a uniform disk. They are consistent with the polar darkening observed by the Pioneer Venus

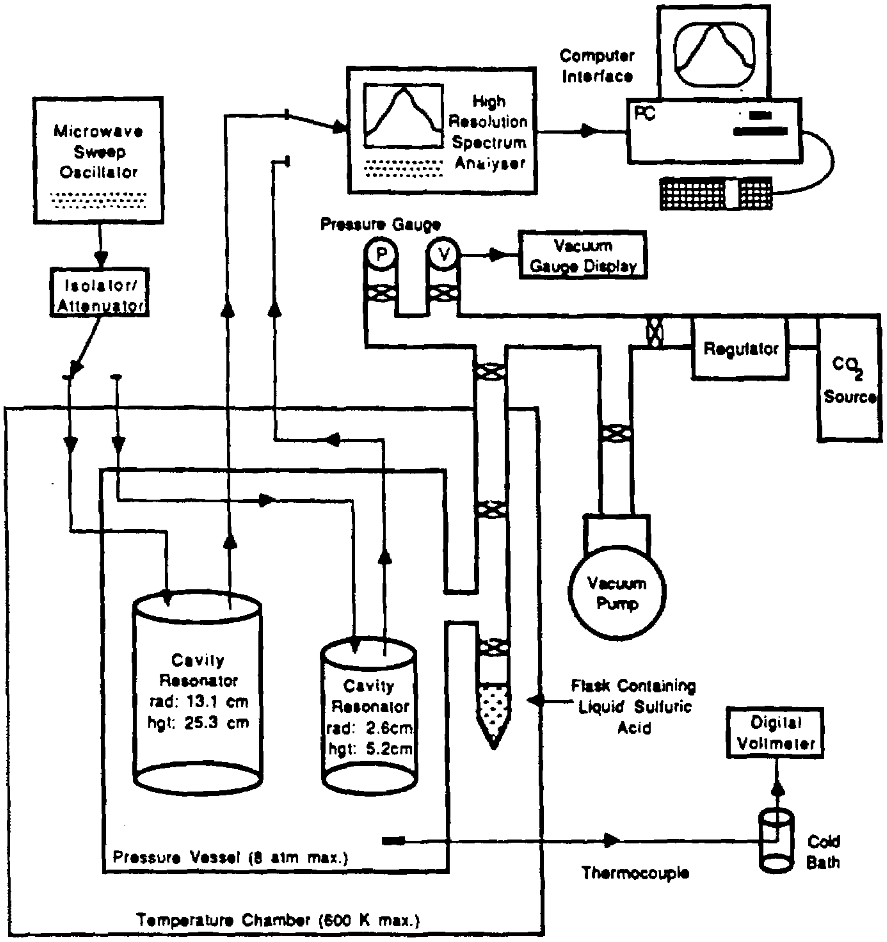
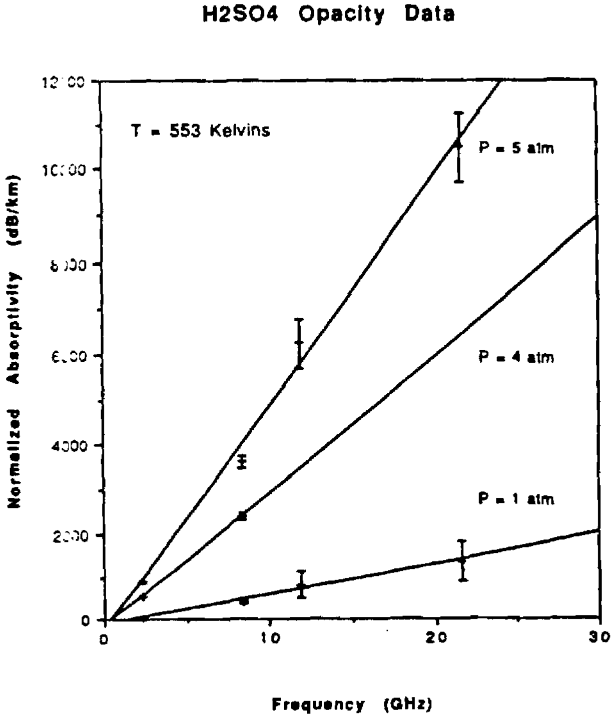
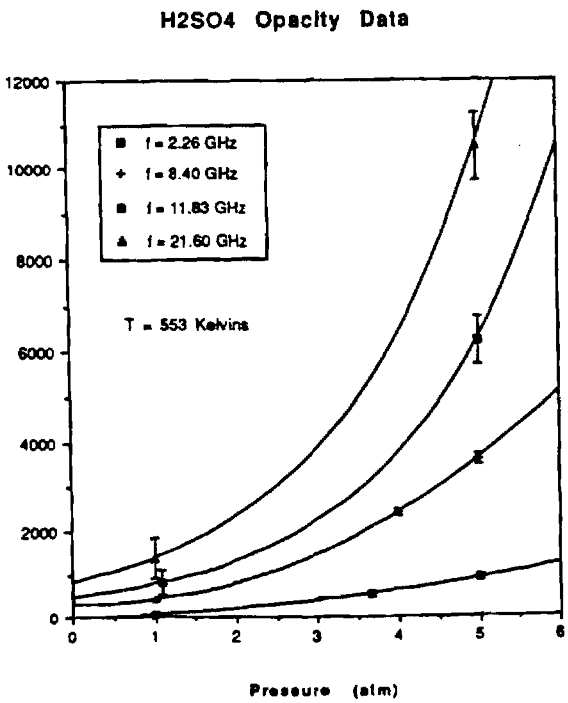


Fig.1:
Block diagram of the atmospheric simulator, as configured for measurements of the microwave absorption of gaseous sulfuric acid under Venus atmospheric conditions.

Fig 2 (below): Measured absorptivity (normalized by mixing ratio) of gaseous H_2SO_4 in a CO_2 atmosphere as a function of pressure and frequency.





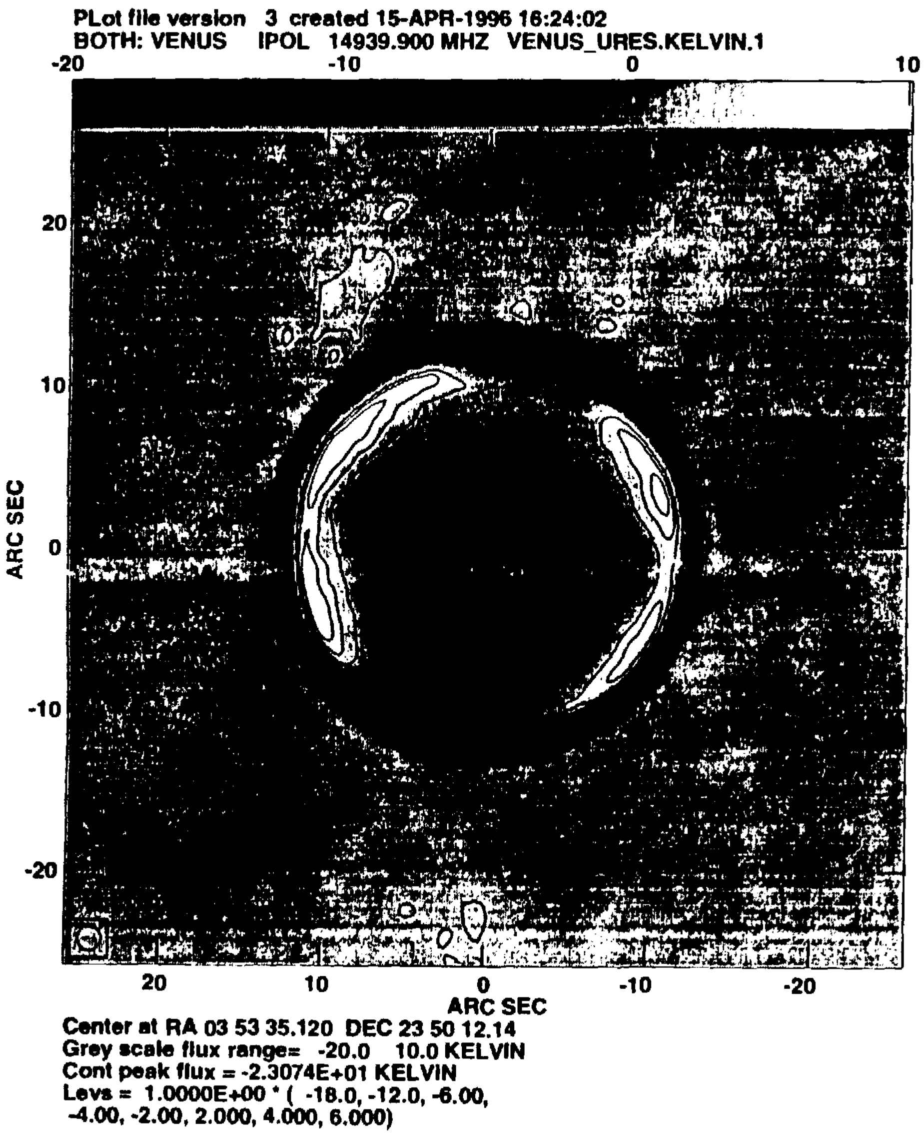


Figure 3: Map of 2 cm Venus emission (residual relative to emission from uniformly opaque sphere.)

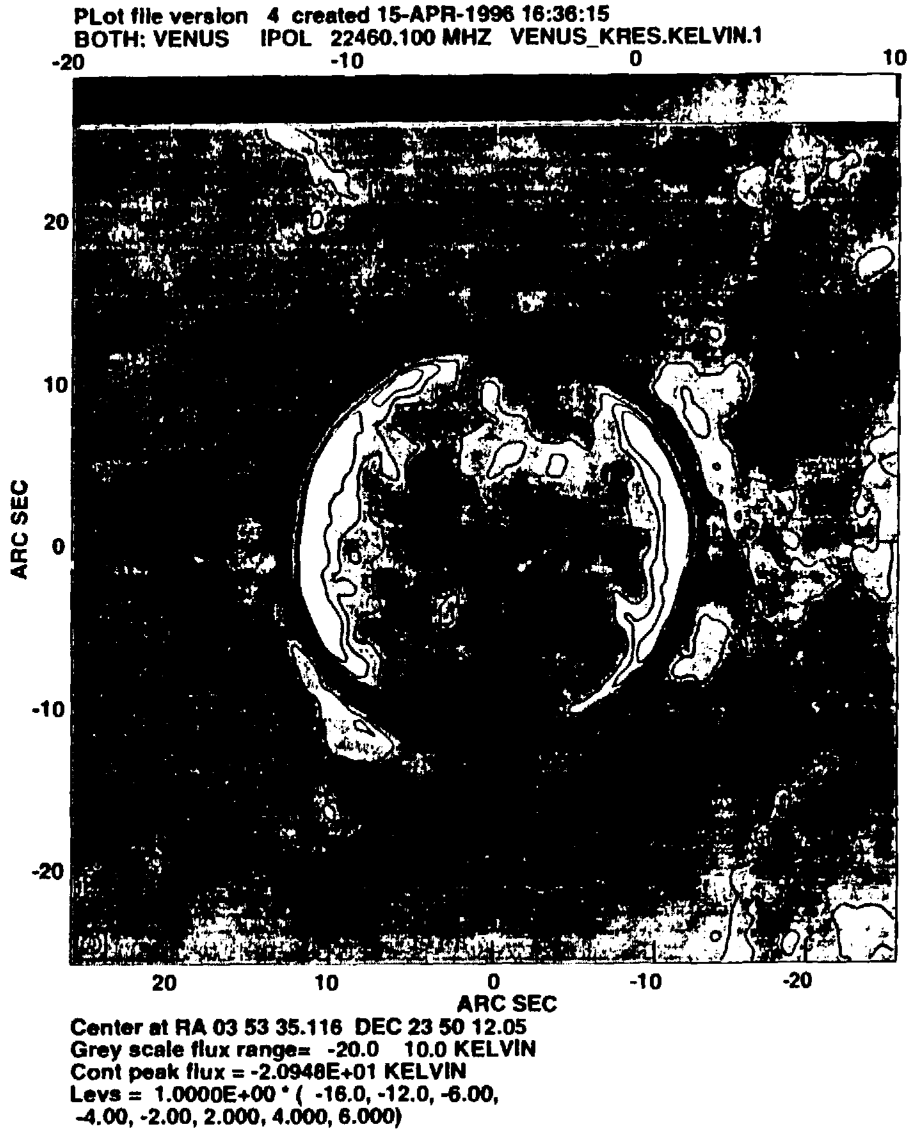


Figure 4: Map of 1.3 cm Venus emission (residual relative to emission from uniformly opaque sphere.)

Orbiter Infrared Radiometer (OIR) experiment (Taylor, et al., 1980). These emission maps will be interpreted using our radiative transfer models, which will incorporate the new formalisms for the opacity from SO_2 and gaseous H_2SO_4.

C. OTHER ACCOMPLISHMENTS

In October 1995, three (3) conference presentations were made at the 1995 AAS/DPS meeting (Kolodner and Steffes, 1995; Suleiman and Steffes, 1995; and DeBoer and Steffes, 1995). The abstracts for these presentations are attached as Appendix B. Two refereed journal papers were also published: Suleiman et al. (1996, reprints previously mailed) and DeBoer and Steffes (1996a, reprints will be mailed when received from publisher). A third refereed paper (DeBoer and Steffes, 1996b) has recently been accepted for publication in Icarus. (Preprints were previously mailed) Additionally, the 1996 IEEE Judith A. Resnik Award was presented to the Principal Investigator of this grant with the citation, "for contributions to an understanding of the Venus atmosphere through innovative microwave measurements," acknowledging work accomplished under this grant.

III. PLANNED WORK FOR THE UPCOMING GRANT YEAR
(November 1, 1996 - October 31, 1997)

Once the high-accuracy laboratory measurements of the absorptivity and refractivity of gaseous H_2SO_4 are completed, an analytical formalism will be developed, using the existing Poynter/Pickett/Cohen line catalog (1994), which will allow accurate computation of the opacity of the H_2SO_4 under Venus conditions. The formalism to be developed fits the laboratory data to the combined effects of all 55,563 lines by selecting the proper lineshape formalism (Van Vleck-Weisskopf, Ben Reuven, Gross, etc.), in a similar fashion to that used previously to develop formalisms for SO_2 (Suleiman, et al., 1996).

The new formalism will be directly applied to the 13 cm Magellan absorptivity profiles (after subtracting the known absorption from CO_2) to develop high accuracy H_2SO_4 abundance profiles for the Venus atmosphere. Additionally, by using the new profiles and our formalism, we can subtract the effects of the absorption of H_2SO_4 (and CO_2) from the 3.6 cm absorptivity profiles and be left with only absorption due to SO_2, which will then be used to derive SO_2 abundance profiles, using the new formalism we have developed for SO_2 opacity (Suleiman et al., 1996). Details of the new H_2SO_4 formalism will, of course, be published and also provided to investigators working with Venus absorptivity data (e.g. Jenkins at SETI Institute/NASA Ames) so as to be used in developing their new results.

Of equal interest will be the application of this formalism to our microwave radiative transfer model for Venus. A new model for the microwave emission from Venus has been developed by Graduate Student, Mark Kolodner, which is innovative in its full analysis of the effects of atmospheric refraction on limb emission and in its use of Magellan results for modelling the centimeter wavelength surface emission. The first application of this model was described in Suleiman et al. (1996) where the model used the new fomalism for SO_2 absorption to place limits on the abundance of SO_2 in the Venus atmosphere, based on disk-averaged observations of the centimeter-wavelength emission.

One key result of the new modeling effort is the determination that the 20-25 GHz range is the most sensitive portion of the Venus microwave emission spectrum to subcloud SO_2. This is significant in that it includes the 1.3 cm wavelength observed with the VLA. Thus, new maps of the 1.3 cm Venus emission can be used to detect spatial variations in the abundance and distribution of SO_2. Similarly, based on our new model for the opacity from gaseous H_2SO_4, it appears as if the 2 cm wavelength emission is especially sensitive to sub-cloud abundance of gaseous H_2SO_4. Thus, the new 2 cm emission maps will be interpreted using our radiative transfer model incorporating the new formalisms for the opacity from SO_2 and gaseous H_2SO_4.

Finally, after the laboratory measurements of gaseous H_2 SO_4 are complete, the measurement system will be re-constructed in preparation for measurements of the microwave properties of phosphine (PH_3) under simulated Neptune conditions.

Results from both the laboratory studies and observational work will be presented at the 28th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society in Tucson, AZ (October 23-26, 1996). These results will also be submitted for publication in Icarus .

IV. PROPOSED BUDGET

PRINCIPAL INVESTIGATOR: Paul G. Steffes (Georgia Institute of Technology)

TITLE: Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres

GRANT NUMBER: NAGW-533
For the period of November 1, 1996 through
October 31, 1997 (Second year of 3-year program)

ESTIMATED COST BREAKDOWN

I.	DIRECT SALARIES AND WAGES*:			$ 41,260
	A.	Principal Investigator Paul G. Steffes 22% time, calendar year (.20 person-years)	$ 22,329	
	B.	1 Graduate Student (. S. H. Suleiman) 50% time, calendar year (.5 person-years)	$ 15,900	
	C.	1 Senior Administrative Secretary 12% time, calendar year (.12 person-years)	$ 3,031	
II.	FRINGE BENEFITS**:	24.8% of Direct Salaries & Wages (less students)		$ 6,289
III.	MATERIALS, SUPPLIES, AND SERVICES			$ 1,500
	A.	Gases, liquids, and supplies (microwave connectors and o-rings) for Experiments	$ 900	
	B.	Miscellaneous Project Supplies (data storage media) and page charges	$ 600	
IV.	TRAVEL			$ 1,300
	A.	Travel for Student to AAS/DPS Meeting (Boston, MA, 5 days duration, airfare $600 plus registration and $ 100/day)	$ 1,300	
		SUBTOTAL - ESTIMATE OF DIRECT COSTS:		$ 50,349
V.	OVERHEAD (Indirect Expense)**: 43% of Modified Total Direct Cost Base			$21,651
	TOTAL FIRST YEAR BUDGET REQUESTED FROM NASA:		$72,000	

SUMMARY OF STAFFING REQUEST: SEE SECTION I (ABOVE)

* The salary and wage rates are based on FY97 salaries for the Georgia Institute of Technology. The Georgia Tech Fiscal Year is July 1 through June 30.

** Rates are for the period July 1, 1996 through June 30, 1997 and are subject to adjustment upon DCAA audit and ONR negotiations.

V. REFERENCES

DeBoer, D. R. and P. G. Steffes, 1995. "Potential Effect of Phosphine (PH3) on the Microwave and Millimeter Wave Opacity and Emission from the Atmosphere of Neptune." Bulletin of the American Astronomical Society, 27, 108. Presented at the 26th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Kona, HI, October 10, 1995.

DeBoer, D. R. and P. G. Steffes, 1996a. The Georgia Tech high sensitivity microwave measurement system. Astrophysics and Space Science 236, 111-124.

DeBoer, D. R. and P. G. Steffes, 1996b. Estimates of the tropospheric vertical structure of Neptune based or radiative transfer studio, in press.

Ho, W., I. A. Kaufman, and P. Thaddeus, 1966. Laboratory measurements of microwave absorption in models of the atmosphere of Venus. J. Geophys. Res. 71, 5091-5108.

Kolodner, M. A., and P. G. Steffes, 1995. "New Laboratory Measurements of the Microwave Opacity of Sulfuric Acid under Simulated Venus Conditions." Bulletin of the American Astronomical Society, 27, 1071-17072. Presented at the 27th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Kona, HI, October 9, 1995.

Poynter, R. L. , H. M. Pickett, and E. A. Cohen, 1994. Submillimeter, millimeter and microwave spectral line catalog. Available on-line via FTP from JPL. Described by Poynter, R. L. and H. M. Pickett, 1985 (same title), Applied Optics 24, 2235-2240.

Suleiman, S. H., and P. G. Steffes, 1995. "Radiative Transfer Models for Venus Microwave and Millimeter-Wave Emission using a Ben-Reuven Formalism for SO_2 Absorption". Bulletin of the American Astronomical Society 27, 1071. Presented at the 27th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Kona, HI, October 9, 1995.

Suleiman, S. H., M. A. Kolodner, and P. G. Steffes, 1996. Laboratory measurement of the temperature dependence of gaseous sulfur dioxide (SO_2) microwave absorption with application to the Venus atmosphere. Journal of Geophysical Research (Planets) 101, 4623-4635.

Taylor, F. W., R. Beer, M. T. Chahine, D. J. Diner, L. S. Elson, R. D. Haskins, D. J. McCleese, J. V. Martonchik, and P. E. Reichley, 1980, Structure and meteorology of the middle atmosphere of Venus: Infrared remote sensing from the Pioneer Orbiter. Journal of Geophysical Research 85, 7963-8006.

BIOGRAPHICAL SKETCH

PAUL G. STEFFES
PROFESSOR
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332-0250

EDUCATION

S.B.	Electrical Engineering	1977
S.M.	Electrical Engineering Massachusetts Institute of Technology	1977
Ph.D.	Electrical Engineering Stanford University	1982

EMPLOYMENT HISTORY

Massachusetts Institute of Technology, Research Laboratory of Electronics, Radio Astronomy and Remote Sensing Group
Graduate Research Assistant — 1976-1977

Watkins-Johnson Company, Sensor Development, San Jose, California
Member of the Technical Staff — 1977-1982

Stanford University, Electronics Laboratory, Center for Radar Astronomy, Stanford, California
Graduate Research Assistant — 1979-1982

Georgia Institute of Technology, School of Electrical and Computer Engineering, Atlanta, Georgia

Assistant Professor	1982-1988
Associate Professor	1988-1994
Professor	1994-Present

EXPERIENCE SUMMARY

At Massachusetts Institute of Technology

Responsible for development, operation, and data analysis for an 8-channel, 118 GHz radiometer system flown aboard the NASA Flying Laboratory (CV-990) as an engineering model for a meteorological sensing satellite. Duties included hardware development of millimeter-wave, microwave, analog, and A to D segments of the system, in addition to airborne operation and reduction of data. The research resulted in a Master's thesis entitled "Atmospheric Absorption at 118 GHz," detailing the first airborne measurement of high altitude atmospheric absorption in the 2.5 millimeter wavelength range, due to atmospheric oxygen.

At Watkins-Johnson Company

Responsibilities included proposals and system design and development, particularly in the area of millimeter-wave systems. Responsibility for millimeter-wave systems development included government sponsored study and development of ELINT (Electronic Intelligence) and radar warning receiving systems to frequencies as high as 110 GHz, as well as internal company sponsored development projects including a 60 GHz communications system and millimeter-wave downconverters.

At Stanford University

Research was concentrated in the area of microwave radio occultation experiments from Voyager and Mariner spacecraft, with specific interest in microwave absorption in planetary atmospheres. Work included computer-based theoretical development of microwave absorption coefficients for planetary atmospheres, to facilitate the use of radio occultation-derived microwave absorption profiles in determining constituent densities. Additional work included the development of a fully instrumented experimental facility for use in measuring the microwave properties of planetary atmospheres under simulated planetary conditions. The research resulted in a Ph.D. dissertation entitled "Abundances of Cloud-Related Gases in the Venus Atmosphere as Inferred from Observed Radio Opacity."

At Georgia Tech

Research Activities: Principal Investigator of the National Science Foundation Grant, "Remote Sensing of Clouds Bearing Acid Rain." This research studied and designed a microwave/millimeter-wave system for remotely sensing the pH of acidic clouds (1982-1983). Principal Investigator of the NASA Planetary Atmospheres Program, "Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres." This research includes study of the interaction between atmospheric constituents and electromagnetic waves, along with application of these studies to spacecraft and radio telescopic measurements of the microwave absorption in atmospheres of Venus and the outer planets (1984-1998). Principal Investigator of the GTE Spacenet Program, "Satellite Interference Locating System (SILS)." The program involved location of uplink signals on the surface of the earth without disrupting regular satellite operations (1986-1990). Principal Investigator of the Emory

University/Georgia Tech Biomedical Technology Research Center project, "Research in Development of a Non-Invasive Blood Glucose Monitoring Technique." This research involved the use of active infrared systems to determine glucose levels in the human eye and bloodstream (1988-1989), with subsequent support (1990-1991) from Lifescan, Inc. Principal Investigator of the NASA Pioneer Venus Guest Investigator Program, "Pioneer Venus Radio Occultation (ORO) Data Reduction: Profiles of 13 cm Absorptivity." This research inferred 13 cm wavelength absorptivity profiles using the Pioneer Venus Orbiter, and then used such profiles to characterize abundance profiles for gaseous H2SO4 in the Venus atmosphere (1988-1990). Principal Investigator/Team Member of NASA High Resolution Microwave Survey (HRMS). This research involved development and operation of the world's most sensitive receiving system used for a 1-10 GHz Sky Survey (1991-1994). Subsequent support has been provided by the SETI Institute (1994-1997). Developer of atmospheric radio occultation experiments conducted with the Magellan (Venus) Spacecraft (1991-1994). Director of the Ku Band Satellite Earth Station System. Responsible for development of a Ku-band uplink/downlink system for use in inter-university networks (1985-1995). Principal investigator in the NASA/ACTS Propagation Experiments Program (1994-1996). This research involves study of Ka-Band propagation effects.

Teaching Activities: Resource Professor for "Satellite Communications Systems" (graduate course). "Electromagnetics Applications" (undergraduate course covering Smith Charts, waveguides, and antennas), have also taught "Electromagnetics II (electrodynamics), "Signals and Systems," and "Survey of Remote Sensing."

Administrative Activities: Chairman, School of ECE Electromagnetics Technical Group, 1990-1996.

HONORS AND AWARDS

Member, Eta Kappa Nu.
Member, Sigma Xi.
Senior Member, IEEE (Member of 6 IEEE Societies).
Recipient of the Stewart Award (MIT for exceptional contribution to student extra-curricular life, 1977.
Recipient of the Metro Atlanta Young Engineer of the Year Award, presented by the Society of Professional Engineers, 1985.
Recipient of the Sigma Xi Young Faculty Research Award, 1988.
Associate Editor, Journa for Geophysical Research (JGR-Atmospheres), 1984-1989.
Appointed Member of the NASA Management and Operations Working Group for the Planetary Atmospheres Program (1986-1990).
Elected to the Electromagnetics Academy, October 1990.
Recipient of the Sigma Xi Best Faculty Paper Award, 1991.
Recipient of the NASA Group Achievement Award, "For outstanding contribution to the design, development, and operation of the High Resolution Microwave Survey Project, and its successful inauguration," March 1993.
Recipient of the 1996 IEEE Judith A. Resnik Award, "For contributions to an understanding of the Venus atmosphere through innovative microwave measurements," January 1996.

OTHER PROFESSIONAL AFFILIATIONS

Member, American Association for the Advancement of Science.
Member, American Astronomical Society, Division for Planetary Sciences.
Member, American Geophysical Union.
Member, American Institute of Physics.
Member, American Society for Engineering Education.
Elected Member, International Union of Radio Scientists (URSI), Commission J (Radio Astronomy).
Chairman, Atlanta Chapter, IEEE Antennas and Propagation Society and Microwave Theory and Techniques Society, 1986-1988. Director, IEEE Atlanta Section, 1988-1989.
Georgia Tech Chapter, Sigma Xi, Vice President, 1990-1991; President 1991-1992; Past-President, 1992-1993.
Chairman, Publicity Committee, 1993 IEEE International Microwave Symposium.

OTHER PROFESSIONAL ACTIVITIES

Proposal Reviewer for the NASA Planetary Astronomy Program, the NASA Planetary Atmospheres Program, the NASA Planetary Instrument Definition and Development Program, the NASA planetary Data Analysis Programs, the NASA Exobiology Program, and the NSF Communications Research Program.
Reviewer/Referee for Icarus (International Journal of Solar System Studies), Journal of Geophysical Research, Radioscience, IEEE Microwave and Guided Wave Letters, and for several textbooks in the area of electromagnetics.
Consultant to industry in the areas of microwave, millimeter-wave, and RF systems for communications, detection, and monitoring. This includes satellite communications, antenna systems, and propagation.
Expert witness in cases involving antenna/communications system performance, and the effects of environmental factors on such systems.

PATENTS

E. H. Orr and P. G. Steffes, "Method and System for Detecting Water Depth and Piloting Vessels," Patent # 4,757,481, issued July 12, 1988.

R. V. Tarr and P. G. Steffes, "Non-Invasive Blood Glucose Measurement System," Patent #5,243,983, issued September 14, 1993.

PUBLICATIONS

Theses

P. G. Steffes, "A Microwave (UHF) Television Repeater System," S.B. Thesis, Massachusetts Institute of Technology, 1976.

P. G. Steffes, "Atmospheric Absorption at 118 GHz," S.M. Thesis, Massachusetts Institute of Technology, 1977.

P. G. Steffes, "Abundances of Cloud-Related Gases in the Venus Atmosphere as Inferred from Observed Radio Opacity," Ph.D. Dissertation, Stanford University, 1982.

Journal Publications

P. G. Steffes and R. A. Meck, "Prototype Tests Secure Millimeter Communications," Microwave Systems News, vol. 10, pp. 59-68, October 1980.

V. R. Eshleman, D. 0. Muhleman, P. D. Nicholson, and P. G. Steffes, "Comment on Absorbing Regions in the Atmosphere of Venus as Measured by Radio Occultation," Icarus, vol. 44, pp. 793-803, December 1980.

P. G. Steffes and V. R. Eshleman, "Sulfur Dioxide and Other Cloud-Related Gases as the Source of the Microwave Opacity of the Middle Atmosphere of Venus," Icarus, vol. 46, pp. 127-13 1, April 1981.

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P. G. Steffes and V. R. Eshleman, "Sulfuric Acid Vapor and Other Cloud-Related Gases in the Venus Atmosphere: Abundances Inferred from Observed Radio Opacity," Icarus, vol. 51, pp. 322-333, August 1982.

P. G. Steffes, "Millimeter-Wavelength Remote Sensing of Stratospheric Sulfur Dioxide," EOS, vol. 64, pp. 198-199, May 1983.

P. G. Steffes, "Laboratory Measurements of the Microwave Opacity and Vapor Pressure of Sulfuric Acid Under Simulated Conditions for the Middle Atmosphere of Venus," Icarus, vol. 64, pp. 576-585, December 1985.

P. G. Steffes, "Evaluation of the Microwave Spectrum of Venus in the 1.2 to 22 cm Wavelength Range Based on Laboratory Measurements of Constituent Gas Opacities," Astrophysical Journal, vol. 310, pp. 482-489, November 1, 1986.

P. G. Steffes and J. M. Jenkins, "Laboratory Measurements of the Microwave Opacity of Gaseous Ammonia (NH3) Under Simulated Conditions for the Jovian Atmosphere," Icarus, vol. 52, pp. 35-47, October 1987.

J. M. Jenkins and P. G. Steffes, "Constraints on the Microwave Opacity of Gaseous Methane and Water Vapor in the Jovian Atmosphere," Icarus, vol. 76, December 1988.

J. Joiner, P. G. Steffes, and J. M. Jenkins, "Laboratory Measurements of the 7.5-9.38 mm Absorption of Gaseous Ammonia (NH3) Under Simulated Jovian Conditions," Icarus, vol. 81, pp. 386-395, 1989.

W. W. Smith and P. G. Steffes, "Time Delay Techniques for a Satellite Interference Location System," IEEE Transactions on Aerospace and Electronic Systems, vol. 25, pp. 224-231, March 1989.

P. G. Steffes, M. J. Klein, and J. M. Jenkins, "Observation of the Microwave Emission of Venus from 1.3 to 3.6 cm," Icarus, vol. 84, pp. 83-92, March 1990.

J. M. Jenkins and P. G. Steffes, "Results for 13 cm Absorptivity and H2SO4 Abundance Profiles from the Season 10 (1986) Pioneer-Venus Orbiter Radio Occultation Experiment," Icarus, vol. 90, pp. 129-138, March 1991.

W. W. Smith, Jr. and P. G. Steffes, "A Satellite Interference Location System Using Differential Time and Phase Measurement Techniques," IEEE Aerospace and Electronic Systems Magazine, vol. 6, pp. 3-7, March 1991.

A. K. Fahd and P. G. Steffes, "Laboratory Measurement of the Millimeter-Wave Properties of Liquid Sulfuric Acid (H2SO4)," Journal of Geophysical Research (Planets), vol. 96, pp. 17,471-17,476, September 25, 1991.

J. Joiner and P. G. Steffes, "Modeling of the Millimeter-Wave Emission of Jupiter Utilizing Laboratory Measurements of Ammonia (NH3) Opacity," Journal of Geophysical Research (Planets), vol. 96, pp. 17,463-17,470, September 25, 1991.

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A. K. Fahd and P. G. Steffes, "Laboratory Measurements of the Microwave and Millimeter-Wave Opacity of Gaseous Sulfur Dioxide (SO2) under Simulated Conditions for the Venus Atmosphere," Icarus, vol. 97, pp. 200-210, June 1992.

A.J. Gasiewski and P.G. Steffes, "University Profile: The Laboratory for Radioscience and Remote Sensing at the Georgia Institute of Technology, IEEE Geoscience and Remote Sensing Society Newsletter, vol. 88, pp. 16-21, September 1993.

J. Joiner, P. G. Steffes, and K. S. Noll, "Search for Sulfur (H2S) on Jupiter at Millimeter Wavelengths," IEEE Transactions on Microwave Theory and Techniques, vol. 40, pp. 1101-1109, June 1992.

P. G. Steffes and D. R. DeBoer, "A SETI Search of Nearby Solar-Type Stars at the 203 GHz Positronium Hyperfine Resonance," Icarus , vol. 107, pp. 215-218, January, 1994.

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VLA OBSERVING APPLICATION

A

rcvd:

DEADLINES: 1st of Feb., June., Oct. for next configuration following review
INSTRUCTIONS: Each numbered item must have an entry or N/A
SEND TO: Director NRAO, 520 Edgemont Rd., Charlottesville, VA 22903-2475

(1) Date Prepared: September 25, 1995

(2) Title of Proposal: Mapping SO_2 and H_2SO_4 on Venus.

(3) AUTHORS	INSTITUTION	Who Will Come To The VLA?	For Grad Students Only: Observations For Ph.D. Thesis?	For Grad Students Only: Anticipate Ph.D. Year
Shady H. Suleiman	Georgia Institute of Technology	X	Yes	1996
Marc A. Kolodner	Georgia Institute of Technology	X	Yes	1996
Dr. Bryan Butler	National Radio Astronomy Observatory	X		
Prof. Paul G. Steffes	Georgia Institute of Technology			

(4) Related VLA previous proposal number(s): AS330

(5) Contact author for scheduling: Prof. Paul G. Steffes
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(7) Scientific Category: ○ astrometry,geodesy & techniques, ○ solar, ○ propagation, ⊗ planetary, ○ stellar, ○ pulsar, ○ ISM, ○ galactic center, ○ galactic structure & dynamics (HI), ○ normal galaxies, ○ active galaxies, ○ cosmology

(8) Configurations (one per column) (A, B, C, D, BnA, CnB, DnC, Any)	C				
(9) Wavelength(s) (400, 90, 20, 18, 6, 3.5, 2, 1.3, 0.7 cm)	1.3 and 2 cm				
(10) Time requested (hours)	12				

(11) Type of observation: ⊗ mapping, ○ point source, ○ monitor, ⊗ continuum, ○ lin poln, ○ circ poln, ○ solar, ○ VLB
(check all that apply) ○ spectroscopy, ○ multichannel continuum, ○ phased array, ○ pulsar, ○ high-time resolution
○ other____________________

(12) ABSTRACT (Do not write outside this space. Please type.)

A VLA observation of Venus is proposed to obtain high resolution continuum maps at frequencies of 15 GHz and 22 GHz. These emission maps will be used to detect potential spatial (logitudinal and latitudinal) variations in the abundances of gaseous sulfur dioxide (SO_2) and gaseous sulfuric acid (H_2SO_4) across the disk of the planet. The suggested observation time is in early April 1996 while the VLA is in the C-configuration. The time requested for this observation is 12 hours which can be divided on two consecutive days (6 hours per day).

NRAO use only

(13) Observer present for observations? ⊗ Yes ○ No Data reduction at? ○ Home ⊗ AOC or CV (2 weeks notic

(14) Help required: ⊗ None ○ Consultation ○ Friend (extensive help)

(15) Spectroscopy Only:

	line 1	line 2	line 3	line 4
Transition (HI, OH, etc.)				
Rest Frequency (MHz)				
Velocity (km/s)				
Observing frequency (MHz)				
Correlator mode				
IF bandwidth(s) (MHz)				
Hanning smoothing (y/n)				
Number of channels per IF				
Frequency Resolution (kHz/channel)				
Rms noise (mJy/bm, nat. weight., 1 hr)				
Rms noise (K, nat. weight., 1 hr)				

(16) Number of sources 1 (If more than 10 please attach list. If more than 30 give only selection criteria and LST range(s).)

(17) NAME	Epoch: 1950 ○ 2000 ⊗ RA hhmm	Dec ± xx.x°	Config.	Band (cm)	Band-width (MHz)	Total Flux line (Jy)*	Total Flux cont. (Jy)	Largest angular size	Required rms (mJy/bm)	Time requested (hours)
Venus	3 37	22.7	C	1.3	50	N/A	86	28″	0.0724	12
			C	2	50	N/A	39	28″	0.0416	

*this should be the total flux at the peak of the line

Notes to the table (if any): Observation will be conducted at 15 GHz (2 cm) and 22 GHz (1.3 cm) simultaneously.

(18) Restrictions to elevation (other than hardware limits) or HA range (give reason): None

(19) Preferred range of dates for scheduling (give reason): Preferred: April 1-15, 1996. Acceptable: Feb. 9-April 15, 1996.

(20) Dates which are not acceptable: All other times.

(21) Special hardware, software, or operating requirements: N/A

(22) Please attach a self-contained Scientific Justification not in excess of 1000 words. (Preprints or reprints will be IGNORED! Please include the full addresses (postal and e-mail) for first-time users or for those that have moved (if not contact author). When your proposal is scheduled, the contents of the cover sheets become public information (Any supporting pages are for refereeing only).

We propose to observe Venus using the Very Large Array (VLA) at 15 GHz and 22 GHz simultaneously. The objective of this observation is to obtain high resolution continuum maps of Venus. These emission maps will be used to detect potential spatial (longitudinal and latitudinal) variations in the abundances of gaseous sulfur dioxide (SO_2) and gaseous sulfuric acid (H_2SO_4) across the disk of the planet. Statistically significant large-scale variations in the 13 cm absorptivity profiles of the sub-cloud Venus atmosphere were observed from the Pioneer-Venus radio occultation data (Jenkins et al., 1991). In addition, small-scale variations in the 3.6 cm and 13 cm opacity profiles were detected from the 1991 Magellan radio occultation measurements (Jenkins et al., 1994). Finally, small and large-scale variations in the emission from the lower atmosphere of the planet were observed in the near infrared images of the nightside of Venus during the Galileo encounter (Carlson et al., and Crisp et al., 1991). These features are likely caused by variations in the sulfur-bearing gases in the lower Venus atmosphere where strong dynamical forces are present.

The frequencies of observation were selected based on their sensitivity to these constituents, as determined using our radiative transfer model. This model incorporates a newly developed Ben-Reuven formalism which provides a more accurate characterization of the microwave absorption of gaseous SO_2 [Suleiman et al., 1995]. The model also uses the most current spectral line catalog [Poynter et al., 1994] to compute the microwave absorption of gaseous H_2SO_4. A 150 ppm mixing ratio of gaseous SO_2 below the main cloud layer (based on uniform mixing) is used which is in agreement with recent infrared Earth-based observations [see Bezard et al., 1993]. This SO_2 mixing ratio also compares well with previous spacecraft in situ measurements [see Oyama et al., 1980 and Gelman et al., 1979]. A 20 ppm mixing ratio of gaseous H_2SO_4 between 38 and 48 km is used which is consistent with the results from the 1991 Magellan radio occultation experiments [see Jenkins et al., 1994]. Figure 1 shows the range of projected differences in the flux density per beam for a viewing angle of 0° (nadir) as a function of frequency between a Venus atmosphere with only carbon dioxide (CO_2), nitrogen (N_2), and water vapor (H_2O) and a Venus atmosphere with CO_2, N_2, H_2O, and SO_2. Figure 2 shows the range of projected differences in the flux density per beam for a viewing angle of 0° (nadir) as a function of frequency between a Venus atmosphere with only CO_2, N_2, H_2O, and SO_2 and a Venus atmosphere with CO_2, N_2, H_2O, SO_2, and H_2SO_4. Note from Figures 1 and 2 that the largest drop in the flux density at nadir due to the absorption from gaseous SO_2 and gaseous H_2SO_4 occurs in the K-band (20-25 GHz) and U-band (12-16 GHz) portions of the emission spectrum, respectively. Thus, simultaneous observations in these regions would be most sensitive to detecting potential spatial variations in the abundances of gaseous SO_2 and gaseous H_2SO_4 which are correlated in position and time and are both contributing to the integrated opacity at each frequency.

Although an observation of the Venus emission was conducted with the VLA in December 1981 at 15 GHz and 22 GHz [Janssen et al., 1982], images obtained at both frequencies had large rms noise levels (± 10 Kelvins or more). Thus, measurements of the effects of gaseous SO_2 at 22 GHz and gaseous H_2SO_4 at 15 GHz from these images were difficult since the possible variations in the brightness temperature are only on the order of 5-10 Kelvins at both frequencies. The current system is significantly more sensitive and thus, less noisy images could be obtained.

We suggest conducting the observation in February through mid April 1996, when the VLA will be in the C-configuration. The apparent angular diameter of Venus will be about 15-30 arc-sec and its distance from Earth will be about 0.7 a.u. The time requested for this observation is 12 hours which can be divided on two consecutive days (6 hours per day), if necessary. This requested time includes both the on-source integration time and the calibration time which is chosen such as to optimize coverage in the U-V plane and hence construct a reasonable continuum image.

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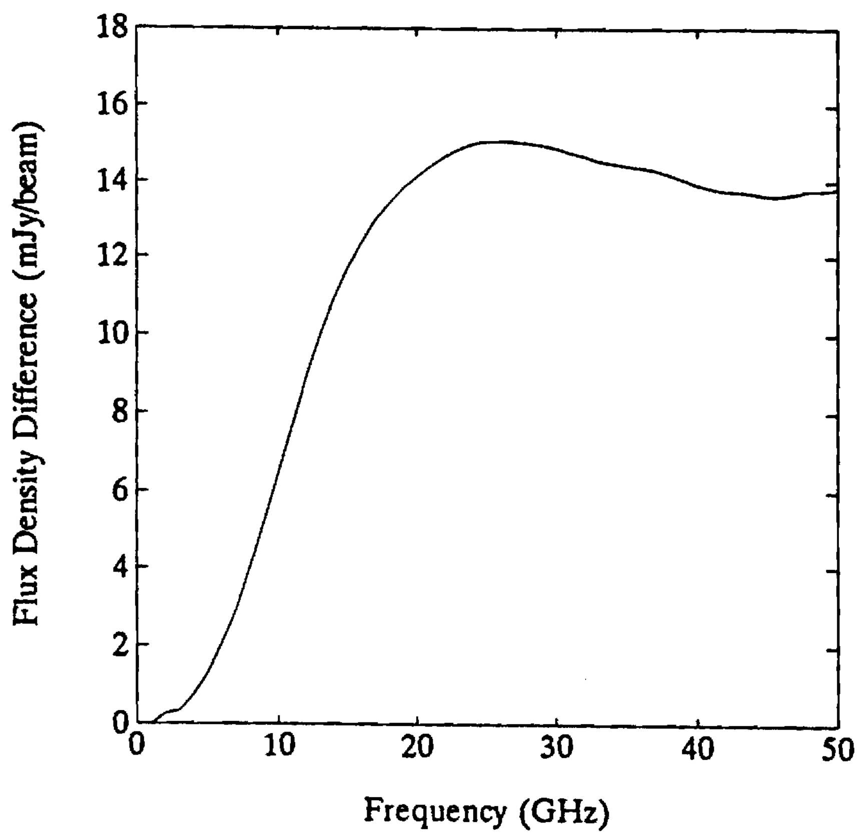

Figure 1: Range of projected differences in the flux density per beam for a viewing angle of 0° (nadir) as a function of frequency between a Venus atmosphere with only CO_2, N_2, and H_2O and a Venus atmosphere with CO_2, N_2, H_2O, and SO_2. The mixing ratio for gaseous SO_2 is 150 ppm (uniformly mixed) below 48 km.

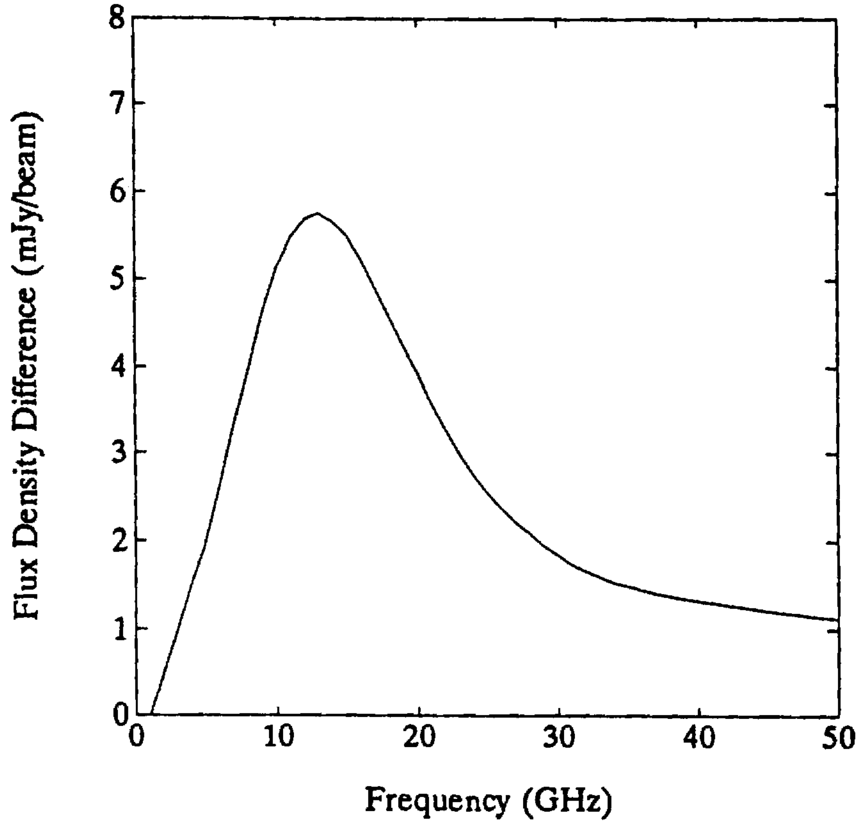

Figure 2: Range of projected differences in the flux density per beam for a viewing angle of 0° (nadir) as a function of frequency between a Venus atmosphere with only CO_2, N_2, H_2O, and SO_2 and a Venus atmosphere with CO_2, N_2, H_2O, SO_2, and H_2SO_4. The mixing ratio for gaseous H_2SO_4 is 20 ppm for altitudes between 38 and 48 km.

New Laboratory Measurements of the Microwave Opacity of Sulfuric Acid Vapor under Simulated Venus Conditions

M. A. Kolodner (School of Physics, Georgia Institute of Technology, Atlanta, Georgia, 30332-0430), P. G. Steffes (School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia, 30332-0250)

New laboratory measurements of the microwave opacity of H_2SO_4 in a CO_2 environment are being performed at 2.25 GHz (13.3 cm), 8.54 GHz (3.5 cm), 16.4 GHz (1.83 cm), and 21.7 GHz (1.38 cm) at a temperature of 590 Kelvins and at pressures ranging from 2 to 6 atmospheres. The experimental setup and approach is similar to that used by Steffes (*Icarus* **64**, p. 576, 1985 & *Astrophys. J.* **310**, p. 482, 1986) but a significant reduction in the uncertainty of the measurements is acheived due to our ability to account for changes in the dielectric properties of the resonators when a lossy gaseous mixture is introduced into them. Based on our absorptivity measurements and the new Poynter-Pickett-Cohen spectral line catalog for H_2SO_4, a new line shape model is being developed. This model, together with a Ben-Reuven line shape model for the microwave opacity of gaseous SO_2 in a CO_2 environment developed by Suleiman et al. (submitted to *JGR Planets*, April 1995), will be incorporated into a radiative transfer model to evaluate the microwave emission spectrum of Venus. Based on radio observations of Venus, new estimates on the disk averaged abundances of gaseous SO_2 and H_2SO_4 vapor in the Venus atmosphere can be inferred. Finally, these microwave opacity models will be used to infer specific abundance profiles of gaseous SO_2 and H_2SO_4 vapor from measured absorptivity profiles of the Venus atmosphere obtained during the 1991 Magellan radio occultation experiments (Jenkins et al., *Icarus* **110**, p. 79, 1994).

This work is being supported by the NASA Planetary Atmospheres Program under grant NAGW-533.

Abstract submitted for DPS [Division for Planetary Sciences] meeting

Date submitted: LPI electronic form version 5/95

Division for Planetary Sciences Abstract Form

DPS Category 3 Running # Session 0.00

Oral preferred [X] Poster preferred [ ] Either [ ]

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Is your abstract newsworthy, and if so, would you be willing to prepare a news release and be available for interviews with reporters?

Yes [ ] No [X] Maybe [ ]

Paper presented by Marc A. Kolodner
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Special instructions:

Membership Status (First Author):

DPS-AAS Member [ ] Non-Member [ ]

Student Member [ ] Student Non-Member [X]

Sponsor: Paul G. Steffes

Radiative Transfer Models for Venus Microwave and Millimeter-Wave Emission using a Ben-Reuven Formalism for SO_2 Absorption

S. H. Suleiman, P. G. Steffes (School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia, 30332-0250)

Several abundance profiles for gaseous sulfur dioxide (SO_2) in the Venus atmosphere have been inferred from spacecraft experiments and Earth-based radio astronomical observations (Oyama *et al.*, *J. Geophys. Res.* 85, 8141-8150, 1980; Hoffman *et al.*, *J. Geophys. Res.* 85, 7882-7890, 1980; Gelman *et al.*, *Space Res.* 20, 219, 1979; Bertaux *et al.*, submitted to *J. Geophys. Res.*, 1995; Bezard *et al.*, *Geophys. Res. Lett.* 20, 15, 1587-1590, 1993; Good and Schloerb, *Icarus* 53, 538-547, 1983; Steffes *et al.*, *Icarus* 84, 83-92, 1990). A radiative transfer model has been developed to examine the effects of these SO_2 abundance profiles on the microwave and millimeter-wave emission of Venus. This model incorporates the newly developed Ben-Reuven line shape formalism (Suleiman *et al.* submitted to *J. Geophys. Res.*, 1995) which provides a more accurate characterization of gaseous SO_2 absorptivity in the Venus atmosphere as compared to other formalisms. The resulting brightness temperature spectra using these abundance profiles are compared with existing observations to examine their consistency. Furthermore, a future observation of Venus using the Very Large Array (VLA) is proposed at 1.3 and 2 cm. This observation along with the measured results from the Magellan radio occulation experiments (Jenkins *et al.*, Icarus 110, 79-94, 1994) will enable us to resolve the spatial and temporal variations of SO_2 abundance in the Venus atmosphere.

This work was supported by the NASA Planetary Atmospheres Program under grant NAGW-533.

Abstract submitted for DPS [Division for Planetary Sciences] meeting

Date submitted: LPI electronic form version 5/95

Division for Planetary Sciences Abstract Form

DPS Category 3 Running # Session 0.00

Oral preferred [X] Poster preferred [ ] Either [ ]

Is this your first DPS presentation? Yes [X] No [ ]

Would you be willing to act as Session Chair? Yes [ ] No [X]

Is your abstract newsworthy, and if so, would you be willing to prepare a news release and be available for interviews with reporters?

Yes [ ] No [X] Maybe [ ]

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Special instructions:

Membership Status (First Author):

DPS-AAS Member [ ] Non-Member [ ]

Student Member [ ] Student Non-Member [X]

Sponsor: Paul G. Steffes

(Enclosure 1)

Proposal No.: 02.105.002.97.001

Principal Investigator: Dr. Paul G. Steffes

Title: Laboratory Evaluation and Application of Microwave Absorption Properties under Simulated Conditions for Planetary Atmospheres

Certification Regarding Debarment, Suspension, and Other Responsibility Matters--Primary Covered Transactions

(1) The prospective primary participant certifies to the best of its knowledge and belief, that it and its principals:

(a) Are not presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department of agency;

(b) Have not within a three-year period preceding this proposal been convicted of or had a civil judgment rendered against them for commission of fraud or a criminal offense in connection with obtaining, attempting to obtain, or performing a public (Federal, State or local) transaction or contract under a public transaction; violation of Federal or State antitrust statutes or commission of embezzlement, theft, forgery, bribery, falsification or destruction of records, making false statements, or receiving stolen property;

(c) Are not presently indicted for or otherwise criminally or civilly charged by a governmental entity (Federal, State or local) with commission of any of the offenses enumerated in paragraph (1)(b) of this certification; and

(d) Have not within a three-year period preceding this application/proposal had one or more public transactions (Federal, State or local) terminated for cause or default.

(2) Where the prospective primary participant is unable to certify to any of the statements in this certification, such prospective participant shall attach an explanation to this proposal.

Certified By:

[signature] 7/10/96

(Signature) (Date)

Janis L. Goddard

(Typed Name)

Contracting Officer

(Title)

Georgia Tech Research Corporation

(Enclosure 1)

CERTIFICATION REGARDING LOBBYING

Certification for Contracts, Grants, Loans, and Cooperative Agreements.

The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No Federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned. to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any Federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooeprative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, "Disclosure Form to Report Lobbying," in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers (including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements) and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000, and not more than $100,000 for each such failure.

Certified by:

Authorized Official (Signature) 7/10/96
Date

Janis L. Goddard
Typed Name

Contracting Officer
Title

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Institution

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Tel: 404 894 3128
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March 26, 1997

Dr. Sethanne Howard
Planetary Atmospheres Program
Code SR
NASA Headquarters
Washington, DC 20546-0001

Dear Dr. Howard:

As specified in the NASA Provisions for Research Grants and Cooperative Agreements, I am enclosing two copies of the Final Report for our Grant NAGW-533 (Laboratory Evaluation and Application of Microwave Absorption Properties under Simulated Conditions for Planetary Atmospheres). As required, I am also forwarding copies of the report, including Appendices, to the NASA Center for AeroSpace Information (CASI).

Our new grant for this project has now been issued by NASA-Goddard Space flight Center and will have an anniversary date of December 31. Thus, our next renewal proposal (which will be for the third year of our current grant cycle) will be sent in August.

Many thanks for your help during this transition.

Sincerely,

Paul G. Steffes
Professor

PGS/mjc

Enclosures

re:a:doc162.pgs

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FINAL REPORT

ENTITLED

LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

to the

Planetary Atmospheres Program of the
National Aeronautics and Space Administration
for Grant NAGW-533

Principal Investigator:
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Report Period: February 1, 1984 through December 31, 1996

Submitted: March 1997

TABLE OF CONTENTS

I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or using laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. Laboratory measurements completed under this grant (NAGW-533), have shown that the opacity from, SO_2 under simulated Venus conditions is best described by a different lineshape than was previously used in theoretical predictions. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements and to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

II. PROGRESS REPORT

This project represents an ongoing activity (since February 1984) to conduct laboratory measurements of the microwave and millimeter-wave properties of simulated planetary atmospheres, in support of NASA missions and ground-based microwave and millimeter-wave observations of planetary atmospheres. The project has also included application of the laboratory results to data from missions and earth-based observations, as well as direct involvement in mission-based microwave measurements (e.g., Magellan atmospheric radio occultation studies) and earth-based measurements (e.g., mapping of Venus with the NRAO/VLA). A renewal project for FY97 funding for this project (November 1, 1996 through October 31, 1997) was submitted to the NASA Planetary Atmospheres Program in July 1996, and has been selected for funding in FY 1997. However, due to the imminent transfer of the grants office at NASA Headquarters, the renewal will be in the form of a new grant issued from the NASA Goddard Space Flight Center, hence, the submission of the Final Report for this grant (NAGW-533).

The technical progress of this project has been described in 22 Progress/Status Reports submitted since 1984. Copies of all reports are available through the NASA Center for AeroSpace Information (NASA-CASI) and are on file at the Planetary Atmospheres Program Office. The current technical status of the project is described in the recent Renewal Proposal and Progress Report #22, which is attached as Appendix A.

III. Students Supported

Over the course of this project, numerous students have been supported as graduate and undergraduate research assistants (see Table I). Additionally, a significant number of student projects, conducted for academic credit, were completed. Nearly every student was involved in the publication of papers in either refereed journals or at conferences, such as AAS/DPS. (See Section IV.) Of the seven Ph.D. students supported by this grant, two have gone on to permanent research positions in planetary and space sciences. Three others have gone to permanent positions in earth atmospheric remote sensing, and two more have taken (or will take) industry positions in space telecommunications. Titles of the Ph.D. dissertations are included in Section IV. of this report.

TABLE I.

Students Supported by Grant NAGW-533

Ph.D.
David R. DeBoer
Antoine K. Fahd
Jon M. Jenkins
Joanna Joiner
Marc A. Kolodner
Shady H. Suleiman
Scott Borgsmiller

M.S.
William Gregory
Gregory Gurski
George O. Hirvela
Jon M. Jenkins
Joanna Joiner
David G. Lashley
Patrick Stellitano
David Watson

B.S.
William Gregory
Jon M. Jenkins
Joanna Joiner
R. Christopher Lott

IV. PUBLICATIONS

The following theses, journal publications, and conference presentations were supported (or partially supported) by Grant NAGW-533.

Ph.D. Dissertations/Theses

J. Joiner, "Millimeter-Wave Spectra of the Jovian Planets," Ph.D. Dissertation, Georgia Institute of Technology, August 1991.

J. M. Jenkins, "Variations in the 13 cm Opacity below the Main Cloud Layer in the Atmosphere of Venus Inferred from Pioneer-Venus Radio Occultation Studied: 1978 - 1987," Ph.D. Dissertation, Georgia Institute of Technology, March 1992.

A. K. Fahd, "Study and Interpretation of the Millimeter-Wave Spectrum of Venus," Ph.D. Dissertation, Georgia Institute of Technology, June 1992.

D. R. DeBoer, "The Microwave Opacity of H_2S with Applications to the Tropospheric Vertical Structure of the Jovian Planets," Ph.D. Dissertation, Georgia Institute of Technology, April 1995.

S. H. Suleiman, "Microwave Effects of Gaseous Sulfuric Dioxide (SO_2) in the Atmosphere of Venus and Earth,"Ph.D. Dissertation, Georgia Institute of Technology, expected May 1997.

M. A. Kolodner, "Microwave Remote Sensing of Sulfuric Acid Vapor in the Venus Atmosphere," Ph.D. Dissertation, Georgia Institute of Technology, expected May 1997.

Journal Publications

P. G. Steffes, "Laboratory Measurements of the Microwave Opacity and Vapor Pressure of Sulfuric Acid Under Simulated Conditions for the Middle Atmosphere of Venus," Icarus, vol. 64, pp. 576-585, December 1985.

P. G. Steffes, "Evaluation of the Microwave Spectrum of Venus in the 1.2 to 22 cm Wavelength Range Based on Laboratory Measurements of Constituent Gas Opacities," Astrophysical Journal, vol. 310, pp. 482-489, November 1, 1986.

P. G. Steffes and J. M. Jenkins, "Laboratory Measurements of the Microwave Opacity of Gaseous Ammonia (NH3) Under Simulated Conditions for the Jovian Atmosphere," Icarus, vol. 52, pp. 35-47, October 1987.

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J. M. Jenkins and P. G. Steffes, "Results for 13 cm Absorptivity and H2SO4 Abundance Profiles from the Season 10 (1986) Pioneer-Venus Orbiter Radio Occultation Experiment," Icarus, vol. 90, pp. 129-138, March 1991.

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J. Joiner and P. G. Steffes, "Modeling of the Millimeter-Wave Emission of Jupiter Utilizing Laboratory Measurements of Ammonia (NH3) Opacity," Journal of Geophysical Research (Planets), vol. 96, pp. 17,463-17,470, September 25, 1991.

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A.J. Gasiewski and P.G. Steffes, "University Profile: The Laboratory for Radioscience and Remote Sensing at the Georgia Institute of Technology, IEEE Geoscience and Remote Sensing Society Newsletter, vol. 88, pp. 16-21, September 1993.

J. Joiner, P. G. Steffes, and K. S. Noll, "Search for Sulfur (H2S) on Jupiter at Millimeter Wavelengths," IEEE Transactions on Microwave Theory and Techniques, vol. 40, pp. 1101-1109, June 1992.

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V. CONCLUSION

Over the 13-year duration of this grant, an effective program integrating microwave and millimeter-wave laboratory measurements with observations conducted from spacecraft experiments and earth-based radio astronomical observations has been conducted. Substantial new results regarding the nature and distribution of tropospheric constituents in the atmospheres of Venus and the outer planets have been obtained. This work was acknowledged by the presentation of the 1996 IEEE Judith A. Resnik Award to the Principal Investigator with the citation, "for contributions to an understanding of the Venus atmosphere through innovative microwave measurements". Similar successes in analysis of the outer planets have also been achieved such as those described in our most recent paper, attached as Appendix B (DeBoer and Steffes, ICARUS, vol. 123, pp. 324-335, October 1996). It is expected that these successes will continue as our new grant from NASA/GSFC commences.

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APPENDIX

RENEWAL PROPOSAL
AND
PROGRESS REPORT #22

ENTITLED

LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

to the

Planetary Atmospheres Program of the
National Aeronautics and Space Administration
for Grant NAGW-533

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Report Period: November 1, 1995 through October 31, 1996

Proposed Renewal Period: November 1, 1996 through October 31, 1997

Submitted: July 1996

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I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occulation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or using laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. For example, laboratory measurements completed recently by Suleiman et al. (1996 reprints previously mailed) under this grant (NAGW-533), have shown that the opacity from, SO_2 under simulated Venus conditions is best described by a different lineshape than was previously used in theoretical predictions. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements and to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

II. PROGRESS REPORT

A. Laboratory Measurements under Simulated Venus Conditions

Over the past five years, we have been active in using the Magellan spacecraft to probe the Venus atmosphere by way of radio occultation studies. One key aspect of the Magellan radio occultation results is the high percentage accuracy of the measured profiles of 13 cm and 3.6 cm absorptivity; typically $\pm$10-15%. To take advantage of these new profiles, so as to develop highly accurate abundance profiles of the microwave absorbing constituents, one must know the microwave absorbing and refracting properties of the constituents very accurately. Carbon dioxide (CO_2) is only a minor contributor to the microwave absorption at both wavelengths, but its absorption properties are well understood (Ho et al., 1966); and since its abundance does not vary significantly in the Venus atmosphere, its effects can be directly subtracted. At 13 cm, the remaining opacity is almost all due to gaseous sulfuric acid (H_2SO_4). Sulfuric acid is, of course, the predominant constituent in the Venus clouds. Understanding the spatial and temporal variations in its gas-phase abundance gives insight into the dynamical processes which affect cloud formation, as well as into the thermochemical processes which constrain the abundances of other reactive constituents in the Venus atmosphere such as COS, H_2O, CO, SO_2, and SO_3. While significant headway has been made in developing a theoretically-derived line catalog of the microwave resonances of H_2SO_4 (see Poynter et al., 1994), large uncertainties in the broadening parameters of the 55,563 microwave lines makes estimates of their combined opacity at 13 cm highly uncertain (~ factor of two).

The best laboratory characterization of the 13 cm opacity from gaseous H_2SO_4 was conducted under this grant in 1984. (Steffes, 1985) The measurements had accuracies of ±50% which far exceeded the accuracies of the opacity data at that time, and dramatically reduced the uncertainties (± factor-of-seven) of previous estimates of gaseous H_2SO_4 opacity. However, now that much better measurements of Venus atmospheric absorptivity have been made, better laboratory measurements are necessary.

In the currently completed grant year (November 1, 1995 - October 31, 1996), we have begun a program to more accurately characterize the microwave absorption properties of sulfuric acid vapor (H_2SO_4) in a CO_2 atmosphere. The approach used in measuring the microwave absorptivity of gaseous H_2SO_4 in a CO_2 atmosphere is similar to those previously used by Suleiman et al. (1996) for the absorptivity of SO_2 in a CO_2 atmosphere under simulated Venus conditions, except that a flask of liquid H_2SO_4 is used to generate the H_2SO_4 vapor, when heated. As can be seen in Figure 1, the absorptivity of the gas mixture is measured by observing the effects of the introduced gas mixture on the Q, or quality factor, of the particular resonances of the two resonators contained in the pressure vessel. The changes in the Q are monitored by the computer-controlled spectrum analysis system, since Q is simply the ratio of the resonant frequency to the half-power bandwidth. Note also that changes in the resonant frequencies themselves are related to the refractivities of the gas mixture at those resonant frequencies, and is likewise important information for the proper interpretation of radio occultation data.

As in our previous work with gaseous H_2SO_4 (Steffes, 1985, 1986), we create a CO_2 / H_2SO_4 mixture by first loading a precisely known volume of liquid H_2SO_4 into the sample flask and then heating the temperature chamber containing the pressure vessel and flask to a high operating temperature (~560K). This assures a large mixing ratio, since it is the vapor which evaporates from the liquid H_2SO_4 which will form part of the mixture. In past experiments, one large source of uncertainty rose from potential changes in the H_2SO_4 mixing ratio caused by reactions with the silver plating on the resonators, which made determination of the actual amount of sulfuric acid vapor difficult. In the new experiments, we have used gold-plated resonators, thus eliminating the effects of reactions.

In Figure 2, the results from the initial absorptivity measurements are shown. These absorptivities are normalized by the sulfuric acid mixing ratio in a CO_2 atmosphere. Additional measurements will be completed by August 1996, so as to develop the most accurate formalism for H_2SO_4 opacity.

B. Venus Observations and Radiative Transfer Modelling

In October 1995, a proposal was submitted to the National Radio Astronomy Observatory (NRAO) for use of the Very Large Array (VLA) for mapping the 1.3 cm and 2 cm emission from Venus. (See Appendix A.) These wavelengths were chosen since they are especially sensitive to the opacity from SO_2 (1.3 cm) and H_2SO_4(2 cm). (See Suleiman et al., 1996 and Kolodner and Steffes, 1995.) The observations were conducted on April 5, 1996 by graduate students Shady H. Suleiman and Marc A. Kolodner, assisted by Dr. Brian Butler from NRAO. Initial inspection of the maps derived from these observations (See Figures 3 and 4) show darkened regions at latitudes greater than 60 degrees. These darkened regions are larger and more pronounced than simple "limb darkened" zones expected from a uniform disk. They are consistent with the polar darkening observed by the Pioneer Venus

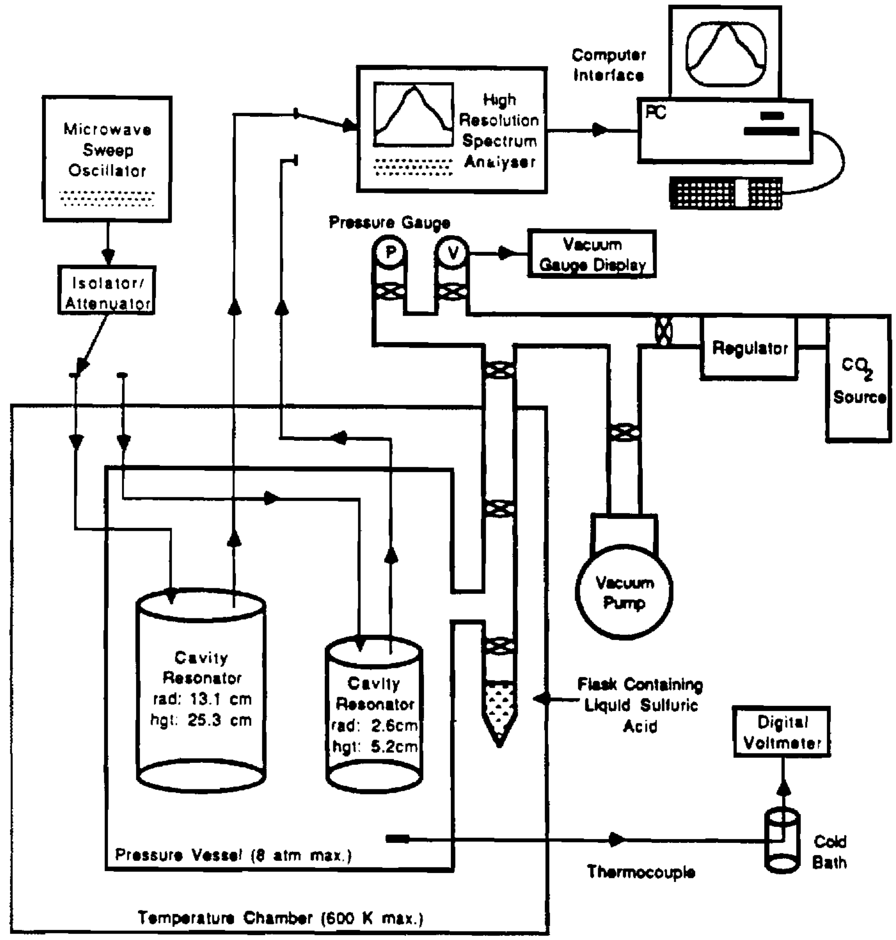
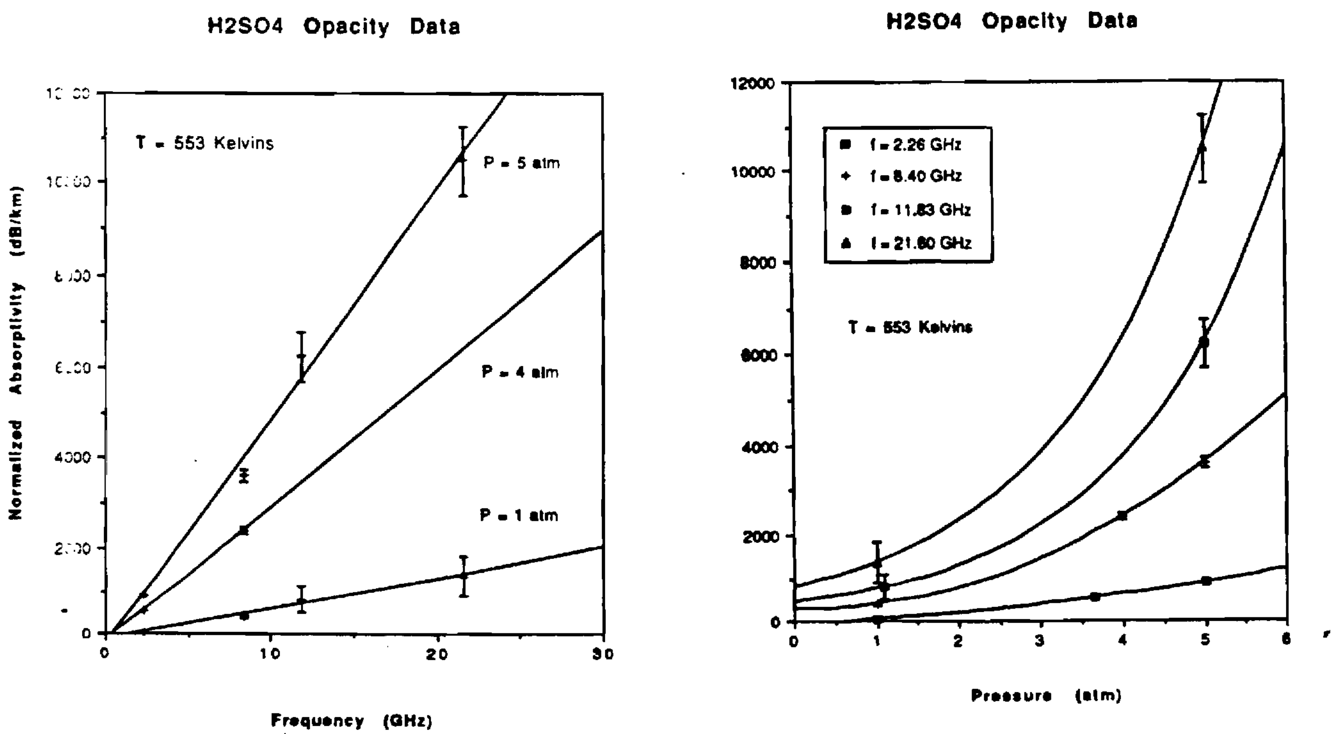


Fig.1:
Block diagram of the atmospheric simulator, as configured for measurements of the microwave absorption of gaseous sulfuric acid under Venus atmospheric conditions.

Fig 2 (below): Measured absorptivity (normalized by mixing ratio) of gaseous H_2SO_4 in a CO_2 atmosphere as a function of pressure and frequency.



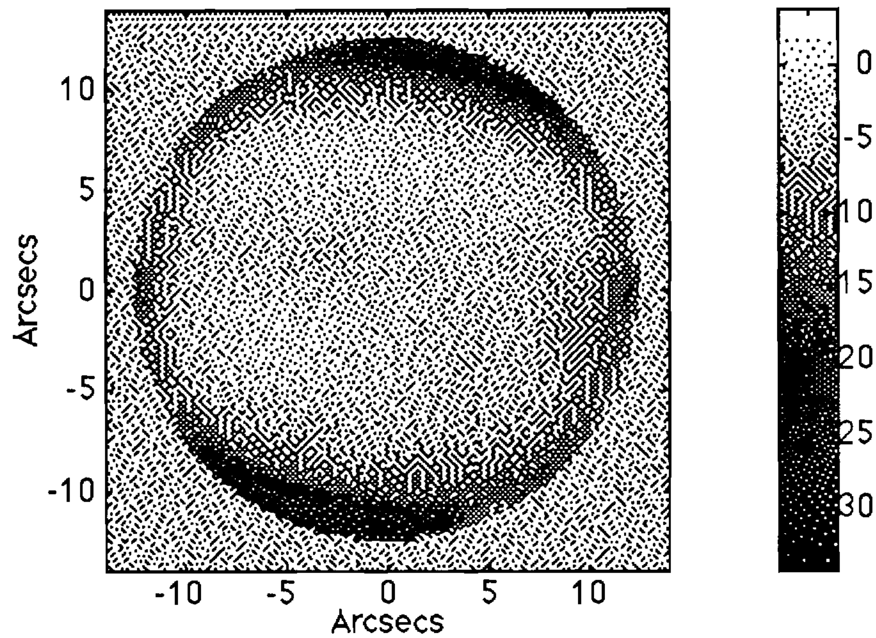


Figure 3: Map of 2 cm Venus emission (residual relative to emission from uniformly opaque sphere.)

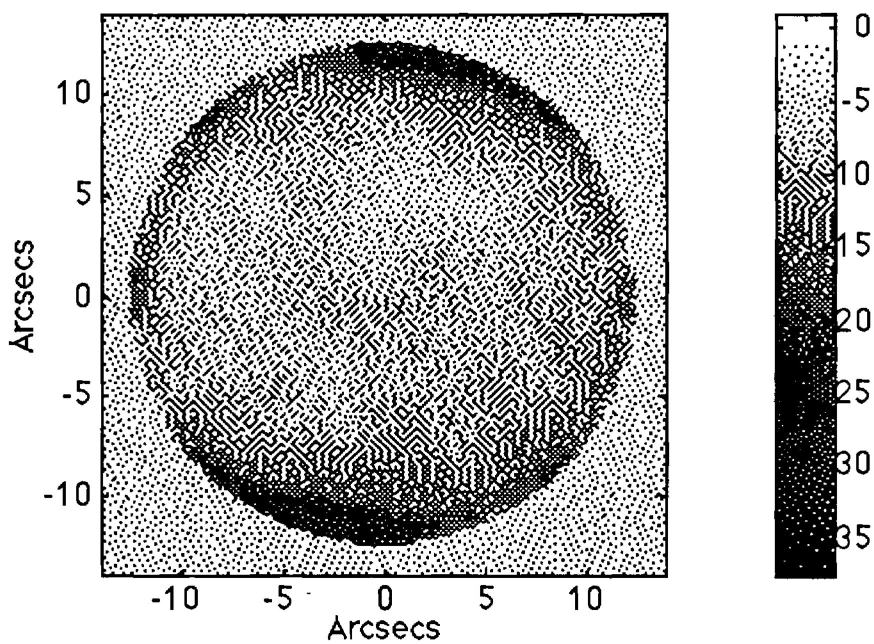


Figure 4: Map of 1.3 cm Venus emission (residual relative to emission from uniformly opaque sphere.)

Orbiter Infrared Radiometer (OIR) experiment (Taylor, et al., 1980). These emission maps will be interpreted using our radiative transfer models, which will incorporate the new formalisms for the opacity from SO_2 and gaseous H_2SO_4.

C. OTHER ACCOMPLISHMENTS

In October 1995, three (3) conference presentations were made at the 1995 AAS/DPS meeting (Kolodner and Steffes, 1995; Suleiman and Steffes, 1995; and DeBoer and Steffes, 1995). The abstracts for these presentations are attached as Appendix B. Two refereed journal papers were also published: Suleiman et al. (1996, reprints previously mailed) and DeBoer and Steffes (1996a, reprints will be mailed when received from publisher). A third refereed paper (DeBoer and Steffes, 1996b) has recently been accepted for publication in Icarus. (Preprints were previously mailed) Additionally, the 1996 IEEE Judith A. Resnik Award was presented to the Principal Investigator of this grant with the citation, "for contributions to an understanding of the Venus atmosphere through innovative microwave measurements," acknowledging work accomplished under this grant.

III. PLANNED WORK FOR THE UPCOMING GRANT YEAR
(November 1, 1996 - October 31, 1997)

Once the high-accuracy laboratory measurements of the absorptivity and refractivity of gaseous H_2SO_4 are completed, an analytical formalism will be developed, using the existing Poynter/Pickett/Cohen line catalog (1994), which will allow accurate computation of the opacity of the H_2SO_4 under Venus conditions. The formalism to be developed fits the laboratory data to the combined effects of all 55,563 lines by selecting the proper lineshape formalism (Van Vleck-Weisskopf, Ben Reuven, Gross, etc.), in a similar fashion to that used previously to develop formalisms for SO_2 (Suleiman, et al., 1996).

The new formalism will be directly applied to the 13 cm Magellan absorptivity profiles (after subtracting the known absorption from CO_2) to develop high accuracy H_2SO_4 abundance profiles for the Venus atmosphere. Additionally, by using the new profiles and our formalism, we can subtract the effects of the absorption of H_2SO_4 (and CO_2) from the 3.6 cm absorptivity profiles and be left with only absorption due to SO_2, which will then be used to derive SO_2 abundance profiles, using the new formalism we have developed for SO_2 opacity (Suleiman et al., 1996). Details of the new H_2SO_4 formalism will, of course, be published and also provided to investigators working with Venus absorptivity data (e.g. Jenkins at SETI Institute/NASA Ames) so as to be used in developing their new results.

Of equal interest will be the application of this formalism to our microwave radiative transfer model for Venus. A new model for the microwave emission from Venus has been developed by Graduate Student, Mark Kolodner, which is innovative in its full analysis of the effects of atmospheric refraction on limb emission and in its use of Magellan results for modelling the centimeter wavelength surface emission. The first application of this model was described in Suleiman et al. (1996) where the model used the new fomalism for SO_2 absorption to place limits on the abundance of SO_2 in the Venus atmosphere, based on disk-averaged observations of the centimeter-wavelength emission.

One key result of the new modeling effort is the determination that the 20-25 GHz range is the most sensitive portion of the Venus microwave emission spectrum to subcloud SO_2. This is significant in that it includes the 1.3 cm wavelength observed with the VLA. Thus, new maps of the 1.3 cm Venus emission can be used to detect spatial variations in the abundance and distribution of SO_2. Similarly, based on our new model for the opacity from gaseous H_2SO_4, it appears as if the 2 cm wavelength emission is especially sensitive to sub-cloud abundance of gaseous H_2SO_4. Thus, the new 2 cm emission maps will be interpreted using our radiative transfer model incorporating the new formalisms for the opacity from SO_2 and gaseous H_2SO_4.

Finally, after the laboratory measurements of gaseous H_2 SO_4 are complete, the measurement system will be re-constructed in preparation for measurements of the microwave properties of phosphine (PH_3) under simulated Neptune conditions.

Results from both the laboratory studies and observational work will be presented at the 28th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society in Tucson, AZ (October 23-26, 1996). These results will also be submitted for publication in Icarus.

IV. PROPOSED BUDGET

PRINCIPAL INVESTIGATOR: Paul G. Steffes (Georgia Institute of Technology)

TITLE: Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres

GRANT NUMBER: NAGW-533
For the period of November 1, 1996 through
October 31, 1997 (Second year of 3-year program)

ESTIMATED COST BREAKDOWN

I.	DIRECT SALARIES AND WAGES*:			$ 41,260
	A.	Principal Investigator Paul G. Steffes 22% time, calendar year (.20 person-years)	$ 22,329	
	B.	1 Graduate Student (. S. H. Suleiman) 50% time, calendar year (.5 person-years)	$ 15,900	
	C.	1 Senior Administrative Secretary 12% time, calendar year (.12 person-years)	$ 3,031	
II.	FRINGE BENEFITS**:	24.8% of Direct Salaries & Wages (less students)		$ 6,289
III.	MATERIALS, SUPPLIES, AND SERVICES			$ 1,500
	A.	Gases, liquids, and supplies (microwave connectors and o-rings) for Experiments	$ 900	
	B.	Miscellaneous Project Supplies (data storage media) and page charges	$ 600	
IV.	TRAVEL			$ 1,300
	A.	Travel for Student to AAS/DPS Meeting (Boston, MA, 5 days duration, airfare $600 plus registration and $ 100/day)	$ 1,300	
		SUBTOTAL - ESTIMATE OF DIRECT COSTS:		$ 50,349
V.	OVERHEAD (Indirect Expense)**: 43% of Modified Total Direct Cost Base			$21,651
	TOTAL FIRST YEAR BUDGET REQUESTED FROM NASA:		$72,000	

SUMMARY OF STAFFING REQUEST: SEE SECTION I (ABOVE)

* The salary and wage rates are based on FY97 salaries for the Georgia Institute of Technology. The Georgia Tech Fiscal Year is July 1 through June 30.
** Rates are for the period July 1, 1996 through June 30, 1997 and are subject to adjustment upon DCAA audit and ONR negotiations.

V. REFERENCES

DeBoer, D. R. and P. G. Steffes, 1995. "Potential Effect of Phosphine (PH3) on the Microwave and Millimeter Wave Opacity and Emission from the Atmosphere of Neptune." Bulletin of the American Astronomical Society, 27, 108. Presented at the 26th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Kona, HI, October 10, 1995.

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VLA OBSERVING APPLICATION

A

rcvd:

DEADLINES: 1st of Feb., June., Oct. for next configuration following review
INSTRUCTIONS: Each numbered item must have an entry or N/A
SEND TO: Director NRAO, 520 Edgemont Rd., Charlottesville, VA 22903-2475

(1) Date Prepared: September 25, 1995

(2) Title of Proposal: Mapping SO_2 and H_2SO_4 on Venus.

(3) AUTHORS	INSTITUTION	Who Will Come To The VLA?	For Grad Students Only: Observations For Ph.D. Thesis?	For Grad Students Only: Anticipate Ph.D. Year
Shady H. Suleiman	Georgia Institute of Technology	X	Yes	1996
Marc A. Kolodner	Georgia Institute of Technology	X	Yes	1996
Dr. Bryan Butler	National Radio Astronomy Observatory	X		
Prof. Paul G. Steffes	Georgia Institute of Technology			

(4) Related VLA previous proposal number(s): AS330

(5) Contact author
for scheduling: Prof. Paul G. Steffes
address: School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, Ga. 30332-0250

(6) Telephone: (404)894-3128
Telex: N/A
Internet: paul.steffes@ee.gatech.edu
Other E Mail: ps11@prism.gatech.edu
Telefax: (404)853-9171

(7) Scientific Category: ○ astrometry,geodesy & techniques, ○ solar, ○ propagation, ⊗ planetary, ○ stellar, ○ pulsar, ○ ISM, ○ galactic center, ○ galactic structure & dynamics (HI), ○ normal galaxies, ○ active galaxies, ○ cosmology

(8) Configurations (one per column) (A, B, C, D, BnA, CnB, DnC, Any)	C				
(9) Wavelength(s) (400, 90, 20, 18, 6, 3.5, 2, 1.3, 0.7 cm)	1.3 and 2 cm				
(10) Time requested (hours)	12				

(11) Type of observation: ⊗ mapping, ○ point source, ○ monitor, ⊗ continuum, ○ lin poln, ○ circ poln, ○ solar, ○ VLB
(check all that apply) ○ spectroscopy, ○ multichannel continuum, ○ phased array, ○ pulsar, ○ high-time resolution
○ other____________

(12) ABSTRACT (Do not write outside this space. Please type.)

A VLA observation of Venus is proposed to obtain high resolution continuum maps at frequencies of 15 GHz and 22 GHz. These emission maps will be used to detect potential spatial (logitudinal and latitudinal) variations in the abundances of gaseous sulfur dioxide (SO_2) and gaseous sulfuric acid (H_2SO_4) across the disk of the planet. The suggested observation time is in early April 1996 while the VLA is in the C-configuration. The time requested for this observation is 12 hours which can be divided on two consecutive days (6 hours per day).

NRAO use only

(13) Observer present for observations? ⊗ Yes ○ No   Data reduction at? ○ Home ⊗ AOC or CV (2 weeks notic

(14) Help required: ⊗ None ○ Consultation ○ Friend (extensive help)

(15) Spectroscopy Only:	line 1	line 2	line 3	line 4
Transition (HI, OH, etc.)				
Rest Frequency (MHz)				
Velocity (km/s)				
Observing frequency (MHz)				
Correlator mode				
IF bandwidth(s) (MHz)				
Hanning smoothing (y/n)				
Number of channels per IF				
Frequency Resolution (kHz/channel)				
Rms noise (mJy/bm, nat. weight., 1 hr)				
Rms noise (K, nat. weight., 1 hr)				

(16) Number of sources 1 (If more than 10 please attach list. If more than 30 give only selection criteria and LST range(s).)

(17) NAME	Epoch: 1950 ○ 2000 ⊗ RA hhmm	Dec ± xx.x°	Config.	Band (cm)	Band-width (MHz)	Total Flux line (Jy)*	Total Flux cont. (Jy)	Largest angular size	Required rms (mJy/bm)	Time requested (hours)
Venus	3 37	22.7	C	1.3	50	N/A	86	28 ″	0.0724	12
			C	2	50	N/A	39	28 ″	0.0416	

*this should be the total flux at the peak of the line

Notes to the table (if any): Observation will be conducted at 15 GHz (2 cm) and 22 GHz (1.3 cm) simultaneously.

(18) Restrictions to elevation (other than hardware limits) or HA range (give reason): None

(19) Preferred range of dates for scheduling (give reason): Preferred: April 1-15, 1996. Acceptable: Feb. 9-April 15, 1996.

(20) Dates which are not acceptable: All other times.

(21) Special hardware, software, or operating requirements: N/A

(22) Please attach a self-contained Scientific Justification not in excess of 1000 words. (Preprints or reprints will be IGNORED! Please include the full addresses (postal and e-mail) for first-time users or for those that have moved (if not contact author). When your proposal is scheduled, the contents of the cover sheets become public information (Any supporting pages are for refereeing only).

We propose to observe Venus using the Very Large Array (VLA) at 15 GHz and 22 GHz simultaneously. The objective of this observation is to obtain high resolution continuum maps of Venus. These emission maps will be used to detect potential spatial (longitudinal and latitudinal) variations in the abundances of gaseous sulfur dioxide (SO_2) and gaseous sulfuric acid (H_2SO_4) across the disk of the planet. Statistically significant large-scale variations in the 13 cm absorptivity profiles of the sub-cloud Venus atmosphere were observed from the Pioneer-Venus radio occultation data (Jenkins et al., 1991). In addition, small-scale variations in the 3.6 cm and 13 cm opacity profiles were detected from the 1991 Magellan radio occultation measurements (Jenkins et al., 1994). Finally, small and large-scale variations in the emission from the lower atmosphere of the planet were observed in the near infrared images of the nightside of Venus during the Galileo encounter (Carlson et al., and Crisp et al., 1991). These features are likely caused by variations in the sulfur-bearing gases in the lower Venus atmosphere where strong dynamical forces are present.

The frequencies of observation were selected based on their sensitivity to these constituents, as determined using our radiative transfer model. This model incorporates a newly developed Ben-Reuven formalism which provides a more accurate characterization of the microwave absorption of gaseous SO_2 [Suleiman et al., 1995]. The model also uses the most current spectral line catalog [Poynter et al., 1994] to compute the microwave absorption of gaseous H_2SO_4. A 150 ppm mixing ratio of gaseous SO_2 below the main cloud layer (based on uniform mixing) is used which is in agreement with recent infrared Earth-based observations [see Bezard et al., 1993]. This SO_2 mixing ratio also compares well with previous spacecraft in situ measurements [see Oyama et al., 1980 and Gelman et al., 1979]. A 20 ppm mixing ratio of gaseous H_2SO_4 between 38 and 48 km is used which is consistent with the results from the 1991 Magellan radio occultation experiments [see Jenkins et al., 1994]. Figure 1 shows the range of projected differences in the flux density per beam for a viewing angle of 0° (nadir) as a function of frequency between a Venus atmosphere with only carbon dioxide (CO_2), nitrogen (N_2), and water vapor (H_2O) and a Venus atmosphere with CO_2, N_2, H_2O, and SO_2. Figure 2 shows the range of projected differences in the flux density per beam for a viewing angle of 0° (nadir) as a function of frequency between a Venus atmosphere with only CO_2, N_2, H_2O, and SO_2 and a Venus atmosphere with CO_2, N_2, H_2O, SO_2, and H_2SO_4. Note from Figures 1 and 2 that the largest drop in the flux density at nadir due to the absorption from gaseous SO_2 and gaseous H_2SO_4 occurs in the K-band (20-25 GHz) and U-band (12-16 GHz) portions of the emission spectrum, respectively. Thus, simultaneous observations in these regions would be most sensitive to detecting potential spatial variations in the abundances of gaseous SO_2 and gaseous H_2SO_4 which are correlated in position and time and are both contributing to the integrated opacity at each frequency.

Although an observation of the Venus emission was conducted with the VLA in December 1981 at 15 GHz and 22 GHz [Janssen et al., 1982], images obtained at both frequencies had large rms noise levels (± 10 Kelvins or more). Thus, measurements of the effects of gaseous SO_2 at 22 GHz and gaseous H_2SO_4 at 15 GHz from these images were difficult since the possible variations in the brightness temperature are only on the order of 5-10 Kelvins at both frequencies. The current system is significantly more sensitive and thus, less noisy images could be obtained.

We suggest conducting the observation in February through mid April 1996, when the VLA will be in the C-configuration. The apparent angular diameter of Venus will be about 15-30 arc-sec and its distance from Earth will be about 0.7 a.u. The time requested for this observation is 12 hours which can be divided on two consecutive days (6 hours per day), if necessary. This requested time includes both the on-source integration time and the calibration time which is chosen such as to optimize coverage in the U-V plane and hence construct a reasonable continuum image.

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[] Suleiman, S. H., M. A. Kolodner, and P. G. Steffes, Laboratory Measurement of the Temperature Dependence of Gaseous Sulfur Dioxide (SO_2) Microwave Absorption with Application to the Venus Atmosphere, Submitted to Journal of Geophysical Research (Planets), March 1995.

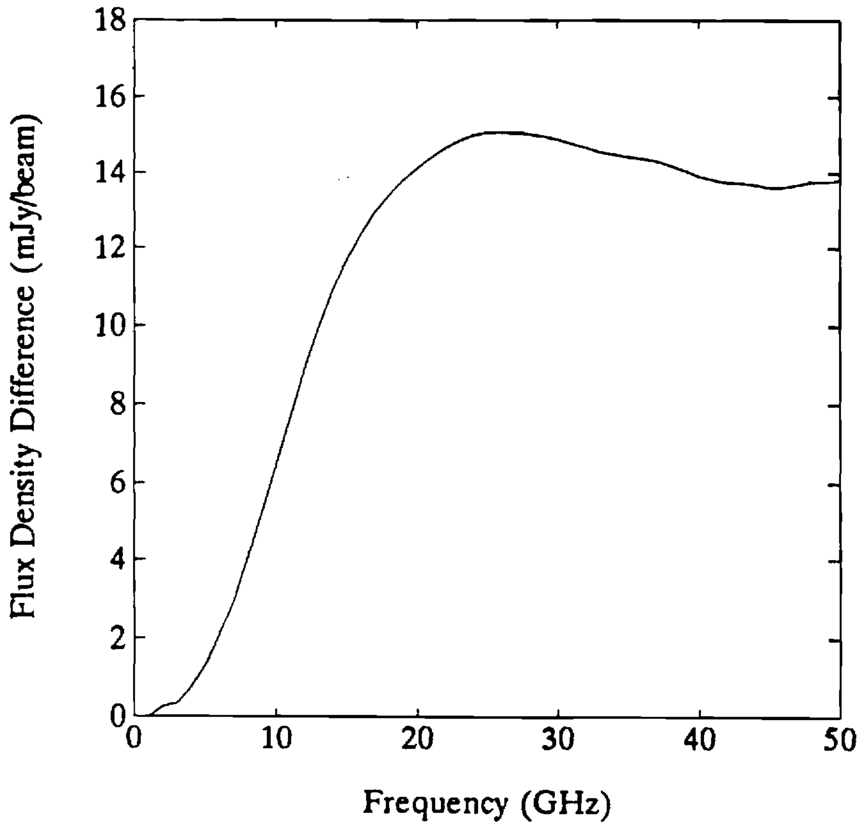

Figure 1: Range of projected differences in the flux density per beam for a viewing angle of 0° (nadir) as a function of frequency between a Venus atmosphere with only CO_2, N_2, and H_2O and a Venus atmosphere with CO_2, N_2, H_2O, and SO_2. The mixing ratio for gaseous SO_2 is 150 ppm (uniformly mixed) below 48 km.

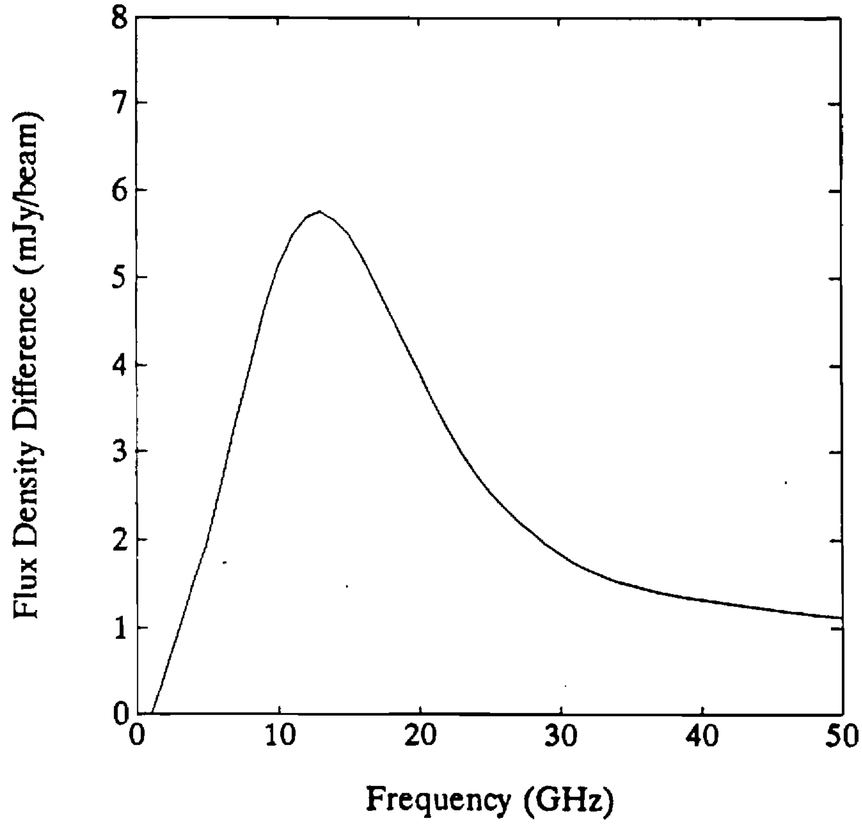

Figure 2: Range of projected differences in the flux density per beam for a viewing angle of 0° (nadir) as a function of frequency between a Venus atmosphere with only CO_2, N_2, H_2O, and SO_2 and a Venus atmosphere with CO_2, N_2, H_2O, SO_2, and H_2SO_4. The mixing ratio for gaseous H_2SO_4 is 20 ppm for altitudes between 38 and 48 km.

New Laboratory Measurements of the Microwave Opacity of Sulfuric Acid Vapor under Simulated Venus Conditions

M. A. Kolodner (School of Physics, Georgia Institute of Technology, Atlanta, Georgia, 30332-0430), P. G. Steffes (School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia, 30332-0250)

New laboratory measurements of the microwave opacity of H_2SO_4 in a CO_2 environment are being performed at 2.25 GHz (13.3 cm), 8.54 GHz (3.5 cm), 16.4 GHz (1.83 cm), and 21.7 GHz (1.38 cm) at a temperature of 590 Kelvins and at pressures ranging from 2 to 6 atmospheres. The experimental setup and approach is similar to that used by Steffes (*Icarus* **64**, p. 576, 1985 & *Astrophys. J.* **310**, p. 482, 1986) but a significant reduction in the uncertainty of the measurements is acheived due to our ability to account for changes in the dielectric properties of the resonators when a lossy gaseous mixture is introduced into them. Based on our absorptivity measurements and the new Poynter-Pickett-Cohen spectral line catalog for H_2SO_4, a new line shape model is being developed. This model, together with a Ben-Reuven line shape model for the microwave opacity of gaseous SO_2 in a CO_2 environment developed by Suleiman et al. (submitted to *JGR Planets*, April 1995), will be incorporated into a radiative transfer model to evaluate the microwave emission spectrum of Venus. Based on radio observations of Venus, new estimates on the disk averaged abundances of gaseous SO_2 and H_2SO_4 vapor in the Venus atmosphere can be inferred. Finally, these microwave opacity models will be used to infer specific abundance profiles of gaseous SO_2 and H_2SO_4 vapor from measured absorptivity profiles of the Venus atmosphere obtained during the 1991 Magellan radio occultation experiments (Jenkins et al., *Icarus* **110**, p. 79, 1994).

This work is being supported by the NASA Planetary Atmospheres Program under grant NAGW-533.

Abstract submitted for DPS [Division for Planetary Sciences] meeting

Date submitted: LPI electronic form version 5/95

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Paper presented by Marc A. Kolodner
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Sponsor: Paul G. Steffes

Radiative Transfer Models for Venus Microwave and Millimeter-Wave Emission using a Ben-Reuven Formalism for SO_2 Absorption

S. H. Suleiman, P. G. Steffes (School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia, 30332-0250)

Several abundance profiles for gaseous sulfur dioxide (SO_2) in the Venus atmosphere have been inferred from spacecraft experiments and Earth-based radio astronomical observations (Oyama *et al.*, *J. Geophys. Res.* 85, 8141-8150, 1980; Hoffman *et al.*, *J. Geophys. Res.* 85, 7882-7890, 1980; Gelman *et al.*, *Space Res.* 20, 219, 1979; Bertaux *et al.*, submitted to *J. Geophys. Res.*, 1995; Bezard *et al.*, *Geophys. Res. Lett.* 20, 15, 1587-1590, 1993; Good and Schloerb, *Icarus* 53, 538-547, 1983; Steffes *et al.*, *Icarus* 84, 83-92, 1990). A radiative transfer model has been developed to examine the effects of these SO_2 abundance profiles on the microwave and millimeter-wave emission of Venus. This model incorporates the newly developed Ben-Reuven line shape formalism (Suleiman *et al.* submitted to *J. Geophys. Res.*, 1995) which provides a more accurate characterization of gaseous SO_2 absorptivity in the Venus atmosphere as compared to other formalisms. The resulting brightness temperature spectra using these abundance profiles are compared with existing observations to examine their consistency. Furthermore, a future observation of Venus using the Very Large Array (VLA) is proposed at 1.3 and 2 cm. This observation along with the measured results from the Magellan radio occulation experiments (Jenkins *et al.*, Icarus 110, 79-94, 1994) will enable us to resolve the spatial and temporal variations of SO_2 abundance in the Venus atmosphere.

This work was supported by the NASA Planetary Atmospheres Program under grant NAGW-533.

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Special instructions:

Membership Status (First Author):

DPS-AAS Member [ ] Non-Member [ ]

Student Member [ ] Student Non-Member [X]

Sponsor: Paul G. Steffes

Potential Effects of Phosphine (PH_3) on the Microwave and Millimeter Wave Opacity and Emission from the Atmosphere of Neptune

D. R. DeBoer (Hughes STX Corp., Greenbelt, MD 20770), P. G. Steffes (School of Elec. and Comp. Eng., Georgia Inst. of Tech., Atlanta, GA 30332-0250)

In order to best match the most reliable disk-averaged microwave and millimeter-wave emission measurements of Neptune (1 mm to 20 cm) and not exceed the measurements of 13 cm and and 3.6 cm absorptivity made by Voyager 2 at Neptune (Lindal, *Astron J.* 103, 967-982), a Neptune atmosphere where the abundance of H_2S is greater than that of NH_3 below the putative NH_4SH cloud in the deep atmosphere is required (DeBoer and Steffes, *B.A.A.S.* 26, 1094, 1994). While such an atmosphere (e.g. 78% H_2, 19% He, 3% CH_4, plus 40 x solar H_2S and 0.2 x solar NH_3) gives an excellent fit to the microwave and millimeter-wave emission spectra, its opacity is too low at 13 cm and 3.6 cm to explain the Voyager radio occultation results. It is possible, however, to match both the emission spectra *and* the Voyager results by adding phosphine (PH_3) to the model.

Phosphine has been detected on Jupiter and Saturn at its strong rotational résonance (267 GHz, see, e.g., Weisstein and Serabyn, *Icarus* 84, 367-381). The results from Saturn inferred a 10x solar abundance. Preliminary estimates with our Neptune radiative transfer model suggest that a PH_3 abundance between 10x and 20x solar best fits the the microwave data. Estimates of the microwave absorption spectrum of PH_3 have been made using the Poynter, Pickett, and Cohen line catalog (available *on-line* from JPL), and assuming Van Vleck-Weisskopf lineshapes with a range of possible broadening parameters. In the future, we plan to conduct laboratory measurements of the cm and mm wave opacity of PH_3 in an H_2/He atmosphere to more accurately predict this effect.

This work has been supported by the NASA Planetary Atmospheres Program under Grant NAGW-533.

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DPS Category 11 Running # Session 0.00

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Special instructions:

Membership Status (First Author):

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Student Member [ ] Student Non-Member [ ]

Sponsor:

Appendix B (pg 3 of 3)